



## GNSS-based Road Charging Systems - Assessment of Vehicle Location Determination

**Zabic, Martina**

*Publication date:*  
2011

*Document Version*  
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

*Citation (APA):*  
Zabic, M. (2011). *GNSS-based Road Charging Systems - Assessment of Vehicle Location Determination*. DTU Transport. PhD-2011-01

---

### General rights

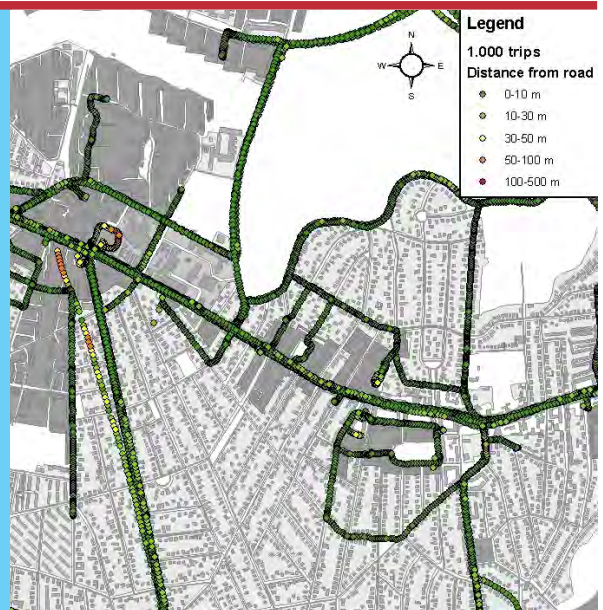
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

# GNSS-based Road Charging Systems

## Assessment of Vehicle Location Determination



Martina Zabic

July 2011

# GNSS-based Road Charging Systems

Assessment of Vehicle Location  
Determination

Martina Zabic

Kgs. Lyngby, 2011

PHD-2011-01  
Department of Transport  
Technical University of Denmark

Copyright: Copying permitted if source is stated.

Published by: DTU Transport  
Bygningstorvet 116B  
DK-2800 Kongens Lyngby  
Denmark

Order at: <http://www.transport.dtu.dk>  
Tel +45 45256500, Fax +45 45936412  
[transport@transport.dtu.dk](mailto:transport@transport.dtu.dk)

ISBN: 978-87-7327-219-0 (Electronic version)

ISBN: 978-87-7327-220-6 (Printed version)

# Abstract

---

An increasing demand for satellite-based road charging systems is developing in Europe. Satellite-based road charging involves charging road users for their road usage by allowing the vehicles to locate themselves within a certain charge area using Global Navigation Satellite Systems (GNSS). The research presented in this thesis deals with the performance and technological challenges of vehicle location determination within GNSS-based road charging systems.

GNSS-based road charging systems may take on a number of different forms. Depending on the charging objective, these road charging systems can be designed in various forms and varied by both policy and technology but they all share the overall function of charging vehicle users for their road usage. The first part of the thesis presents a comprehensive overview and classification of the various forms of road charging systems and enabling technologies; supplemented with a review of different worldwide examples. Next the system fundamentals are defined and presented in a conceptual framework which forms the basis for the research presented in this thesis. In order to understand the structure and behaviour of GNSS-based road charging systems, it is important to highlight the overall system architecture and define the essential system functions and describe the relationship among them. The framework is used as a means to structure the discussion about the technological

challenges of GNSS-based road charging systems.

The thesis discusses the overall performance requirements for the road charging process within GNSS-based road charging systems. GNSS allows for time-distance-place charging, where charges are calculated for each individual vehicle based on the distance driven, the time of the trip and the vehicle's geographic position. Time-distance-place charging is therefore considered a more fair and efficient way of charging as these systems levy charges proportionally to the distance travelled, and thereby reflects a usage-based approach more accurately than other charging policies. However, road charging on the basis of the distance travelled is technically challenging and is seen as one of the most complex schemes. Determining the distance driven is the key part of the charging process and the main dependability concerns therefore revolve around the road charging process and the performance of the vehicle location determination function. The thesis provides a thorough review of the different GNSS-based trials and experiments conducted within recent years to assess the performance and possibilities of GNSS-based charging systems.

In 2007–2009, a GNSS-based road charging experiment was conducted in Copenhagen as part of this research in cooperation with Siemens to assess the performance and technical challenges of GNSS-based road charging systems based on state of the art road charging technology. This thesis presents the experiment conducted and provides an assessment of the vehicle location determination function within GNSS-based road charging systems. Previous trials and performance assessments of GNSS-based road charging systems have generally focused on the possibilities of the charging systems rather than on the impossibilities. Often it has not been clearly described which errors and shortages existed in the collected data, but instead they have just been excluded as invalid data prior to the assessments which then concluded that more focus should be placed on the errors occurred. Hence, it has been deliberate in this PhD research not to exclude faulty and incorrect data in the assessment. The results presented in this thesis are based on all the collected data from the experiment, in its

original for, as it would be used as input for the automated charge calculation process in a road charging system. Furthermore, new methodologies are developed for assessing the performance of the vehicle location determination function in terms of data reliability and navigation function performance. The results from the assessments conducted in this thesis demonstrate that although significant performance improvements have happened during the last five years, there are significant challenges to overcome in relation to implementation and operation of GNSS-based road charging systems. The technical experiment conducted in this PhD study proved to suffer from different technical challenges which had different impacts on the overall system dependability. Due to these challenges, data includes both inaccurate and incomplete data information, and it is hence concluded that with these high levels of data invalidity and deficiency, data could not be used in its current form as basis for a road charging process. These results underline the importance of a data processing functionality prior to the road charge calculation and usage determination in the road charging process.

The assessment of the vehicle location determination function show significant difference in the required navigation performance. While the accuracy requirement in Copenhagen was partly met, the continuity and hence availability required for vehicle location determination suffered from severe gaps in the positioning data. These gaps were due to both satellite unavailability, caused by poor urban signal reception and long receiver acquisition times, and furthermore due to the various technical problems and configuration faults which occurred during the experiment. As both the satellite visibility and the positioning accuracy had improved significantly, the results indicate that the main challenges related to vehicle location determination are not as often stated due to positioning inaccuracies but rather due to a high level of positioning interruptions mainly caused by GPS. From the performance assessment it is furthermore concluded that the main concerns regarding the unavailability of the vehicle location determination should be how to eliminate the large downtime and configuration gaps and reduce the occurrence of the many GPS gaps.

As data outages and failures may affect the determination of the distance driven in continuous charging schemes, the thesis provides means to assess and understand the positioning gap occurrence, contribution and effects in relation to GNSS-based road charging systems. Hence, an assessment of the driven distance determination tolerance towards these different positioning related outages is provided. The assessment is conducted on the basis of a simulation methodology developed in this thesis. It analyzes the influence of positioning gaps on the determination of the driven distance in both distance-based and distance-related GNSS-based road charging schemes. The gap tolerance of the distance determination in both types of charging schemes is important for the road charging system's ability to meet the performance requirements and charge the road users correctly for their road usage. The simulation analyses of the gap influence on the driven distance determination show that the distance determination function is relatively robust against small gaps of less than 10 seconds in the positioning. However, with several medium and large gaps in the trips, both distance determination methods have trouble in reproducing the driven distances with distance deviations more than 1 % from the truth. The importance of these results is that for the majority of trips the distance driven can be determined with less than 1 % distance deviation as the occurrence of small gaps is most frequent in trips.

GNSS-based road charging systems are considered liability-critical systems, where denial of service and undetected fault and failures generate significant legal or economic negative consequences. Any fault or failures that lead to incorrect charging may cause economic loss or provoke wrong legal decisions as the economic liability is associated to the legal aspects due to the repercussion of potential claims. Hence, the thesis introduces the use of system dependability of GNSS-based road charging systems. The concepts of system dependability, adapted from computer engineering, provide an effective means of managing various concerns for road charging systems within a single conceptual framework. Dependability is an important requirement for a GNSS-based road charging system as the system must provide fair charging and gain user trust by



ensuring system reliability and liability. This thesis discusses the impact of the assessment results in relation to system dependability and provides a qualitative dependability risk matrix for the vehicle location determination function.

To ensure high dependability of the road charging process, fault tolerant design should hence be considered in relation to many different components and functionalities within the process. Based on fault tolerant methodologies, this thesis provides guidelines of how to maintain correct service in the presence of different faults caused by technical problems related to vehicle location determination. The main objective of fault tolerant design within the road charging process is to ensure fair charging of the road users. This means that redundant systems, procedures and components should be implemented to ensure that when fault and failures occur within the road charging process, the road charge foundation will still be dependable and provide fair results towards both the road users and the road charging system. This thesis therefore concludes that though the vehicle location determination performance is fair, the focus of the system performance concerns should be placed on how future GNSS-based road charging system can be designed to work reliably with the occurrence of both data invalidity and data deficiency. It is therefore important to widen the focus from technical challenges and component inaccuracies alone to a focus on the system dependability as a whole. There is however still some technological challenges to overcome, which to a greater extent are remediated by better collaboration across the many different subject areas. As with many other ITS systems, a successful design, implementation and operation of a system is only achieved when the many different stakeholders understand each other's requirements to the system. The system architecture as a conceptual design together with the system engineering methodology can help to involve all the different parties in the system development and hence minimize the misunderstandings which at the end can become very costly for the system.

Based on the several findings of this PhD research, some general guidelines are finally formulated for future GNSS-based road

charging systems. The proposed guidelines described in the thesis address both GNSS-based road charging trials in general and a future GNSS-based road charging system in Denmark.

# Resumé

---

En stigende efterspørgsel efter satellitbaserede kørselsafgiftssystemer er på vej i Europa. Satellitbaserede kørselsafgifter omfatter opkrævning af trafikanterne for deres vejforbrug ved at lade køretøjerne bestemme deres position indenfor et givent afgiftsområde ved hjælp af Global Navigation Satellit Systemer (GNSS). Den forskning, der præsenteres i denne afhandling, beskæftiger sig med performanceniveauet samt de teknologiske udfordringer ved bestemmelse af køretøjets placering inden for GNSS-baserede kørselsafgiftssystemer.

GNSS-baserede kørselsafgiftssystemer kan antage en række forskellige former. Afhængigt af systemets formål kan disse kørselsafgiftssystemer være udformet på forskellig vis og varieret efter både politiske og teknologiske hensyn, men de har alle til formål at takserer trafikanterne for deres brug af vejnettet. Den første del af afhandlingen præsenterer en omfattende oversigt og klassificering af forskellige former for kørselsafgiftssystemer samt mulige teknologier, suppleret med en gennemgang af forskellige eksisterende systemer. Efterfølgende defineres det grundlæggende kørselsafgiftssystem og dette sættes ind i en begrebsramme, der danner grundlag for forskningen præsenteret i denne afhandling. For at forstå GNSS-baserede kørselsafgiftssystemers struktur og virkemåde er det vigtigt at fremhæve den overordnede systemarkitektur og definere de væsentlige funktioner samt beskrive forholdet mellem

dem. Arkitekturen er brugt som et middel til at strukturere diskussionen om de teknologiske udfordringer i GNSS-baserede kørselsafgiftssystemer.

Afhandlingen diskuterer de overordnede krav til afgiftsprocessens ydeevne indenfor GNSS-baserede kørselsafgiftssystemer. GNSS muliggør kilometer-baseret afgiftsopkrævning, hvor afgifterne beregnes for hvert enkelt køretøj baseret på den kørte afstand, tidspunktet for turen samt bilens geografiske position. Kilometer-baseret afgiftsopkrævning betragtes derfor som en mere retfærdig og effektiv form for afgiftsopkrævning, da disse systemer opkræver afgiften i forhold til den tilbagelagte afstand, og afspejler dermed den forbrugsbaserede tilgang mere præcist end andre afgiftsopkrævningspolitikker. Men kørselsafgifter på grundlag af den tilbagelagte afstand er teknisk udfordrende og betragtes ofte som en af de mest komplekse ordninger. Fastsættelsen af den faktisk kørte distance er den centrale del af afgiftsopkrævningen, og de vigtigste betænkeligheder omkring pålideligheden vedrører derfor denne del af afgiftsprocessen samt resultaterne af køretøjets lokaliseringsfunktion. Denne afhandling præsenterer endvidere en grundig gennemgang af de forskellige GNSS-baserede forsøg og eksperimenter, der er udført inden for de seneste år, for at vurdere resultater og muligheder ved brug af GNSS-baserede afgiftssystemer.

I 2007–2009 blev et teknisk forsøg med et GNSS-baseret kørselsafgiftssystem udført i København som en del af denne forskning i samarbejde med Siemens. Forsøget blev udført for at vurdere resultater og tekniske udfordringer ved GNSS-baserede kørselsafgiftssystemer baseret på den nyeste kørselsafgiftsteknologi. Denne afhandling præsenterer det udførte eksperiment og giver en vurdering af køretøjets lokaliseringsfunktion inden for GNSS-baserede kørselsafgiftssystemer. Tidligere forsøg og vurderinger af ydeevnen af GNSS-baserede kørselsafgiftssystemer har generelt fokuseret på mulighederne i afgiftssystemerne i stedet for begrænsningerne. Ofte har det ikke været klart beskrevet, hvilke fejl og mangler der eksisterede i de indsamlede data, men i stedet er de blot blevet udelukket som ugyldige data forud for de foretagne vurderinger, som derefter konkluderede, at mere fokus bør lægges på de fundne

fejl. Derfor har det været bevidst i denne ph.d.-forskning, ikke at udelukke fejlagtige og forkerte data i vurderingen af ydeevnen. Resultaterne der er præsenteret i denne afhandling er baseret på alle de indsamlede data fra forsøget, i sin oprindelige form, som det ville være input til den automatiserede afgiftsberegningsproces i et kørselsafgiftssystem. Endvidere er der udviklet nye metoder til vurdering af køretøjets lokaliseringsfunktion i form af datapålidelighed og lokaliseringsfunktionens performance. Resultaterne af vurderingerne foretaget i denne afhandlingen viser, at selvom betydelige performanceforbedringer er sket i løbet af de sidste fem år, er der væsentlige udfordringer at overvinde i forbindelse med implementering og drift af GNSS-baserede kørselsafgiftssystemer. Det tekniske forsøg i dette ph.d.-studie viste sig at lide under forskellige tekniske udfordringer, som havde forskellig indvirkning på den samlede systempålidelighed. På grund af disse udfordringer, omfatter data både unøjagtige og ufuldstændige informationer, og det konkluderes derfor at med disse høje niveauer af datainvaliditet og -mangel, kan data ikke anvendes i sin nuværende form som grundlag for en afgiftsberegningsproces. Disse resultater understreger betydningen af at anvende en dataprocesseringsfunktionalitet før afgiftsberegningen og vejforbrugsbestemmelsen i afgiftsproccessen.

Vurderingen af køretøjets lokaliseringsfunktion viser en signifikant forskel i den ønskede lokaliseringsperformance. Mens nøjagtighedskravet delvist var opfyldt i København, led kontinuiteten og dermed tilgængeligheden nødvendig for bestemmelsen af køretøjets lokalitet af alvorlige udfald i positioneringsdata. Disse udfald skyldtes både satellitutilgængelighed, forårsaget af ringe signalmodtagelse i byområder og lang signalerhvervelsestid hos modtageren, og endvidere de forskellige tekniske problemer og konfigurationsfejl, der opstod under forsøget. Da både satellitsynligheden og positioneringsnøjagtigheden gennem de seneste år er forbedret markant, viser resultaterne at de største udfordringer i forbindelse med bestemmelse af køretøjets lokalitet ikke som ofte antaget, er positioneringsnøjagtigheder, men snarere et højt niveau af positioneringsafbrydelser hovedsageligt forårsaget af GPS. På baggrund af resultatvurderingen konkluderes det endvidere, at de væsentligste

bekymringer vedrørende den manglende tilgængelighed til køretøjets lokaliseringsbestemmelse bør være, hvordan den lange systemnedetid og konfigurationsudfaldene kan fjernes samt hvordan forekomsten af de mange GPS-udfald kan reduceres.

Da dataudfald og -svigt kan påvirke bestemmelsen af den kørte afstand i kontinuerlige afgiftssystemer, giver denne afhandling mulighed for at vurdere og forstå forskellige forekomster, bidrag og effekter af udfald i relation til GNSS-baserede kørselsafgiftssystemer. I denne afhandling præsenteres en vurdering af distancebestemmelsens tolerance overfor disse forskellige positioneringsudfald. Vurderingen er foretaget på grundlag af en simuleringsmetode der er udviklet i denne afhandling. Metoden analyserer indflydelsen af positioneringsudfald i forhold til bestemmelsen af kørte kilometer i både distancebaserede og distancerelaterede kørselsafgiftssystemer. Udfaldstolerancen i afstandsbestemmelsen i begge typer afgiftssystemer er vigtig for kørselsafgiftssystemets evne til at opfylde kravene til ydeevne samt i forhold til at taksere brugerne korrekt for deres vejforbrug. Simuleringsanalyserne af indflydelsen af udfald på bestemmelsen af den kørte afstand viser at afstandsbestemmelsesfunktionen er forholdsvis robust over for småudfald på mindre end 10 sekunder i positioneringen. Men med flere mellemstore og store udfald i turene, har begge afstandsbestemmelsesmetoder svært ved med at reproducere den kørte afstand med afstandsafvigelse på mere end 1 % fra den sande værdi. Det vigtige ved disse resultater er, at den kørte afstand kan fastlægges med mindre end 1 % afvigelse for hovedparten af turene eftersom forekomsten af småudfald er hyppigst i de kørte ture.

GNSS-baserede kørselsafgiftssystemer anses for at være ansvarskritiske systemer, hvor nægtet service samt uopdagede fejl og mangler har betydelige retslige eller økonomiske negative konsekvenser. Fejl eller mangler, der fører til ukorrekt afgiftsopkrævning, kan forårsage økonomiske tab eller føre til forkerte juridiske afgørelser, idet det økonomiske ansvar er knyttet til de juridiske aspekter som følge af potentielle klager. Derfor introducerer denne ph.d.-afhandling anvendelsen af begrebet systempålidelighed i forbindelse med GNSS-baserede kørselsafgiftssystemer. Begrebet systempålide-

lighed, som er tilpasset fra informationsteknologien, er en effektiv metode til håndtering af de forskellige betæneligheder i forbindelse med kørselsafgiftssystemer inden for en fælles begrebsramme. Pålidelighed er en vigtig forudsætning for et GNSS-baseret kørselsafgiftssystem, som skal levere en retfærdig afgiftsopkrævning og sikre brugernes tillid ved at sikre systemets pålidelighed og ansvar. Denne afhandling diskuterer konsekvenserne af vurderingsresultaterne i forhold til systemets driftssikkerhed og præsenterer en kvalitativ risikomatrix for driftssikkerheden af køretøjets lokaliseringsfunktion.

For at sikre afgiftsprocessen en høj driftssikkerhed, skal fejltolerant design derfor overvejes i forhold til de mange forskellige komponenter og funktioner der indgår i processen. Baseret på fejltolerante metoder, giver denne afhandling retningslinjer for hvordan man kan opretholde korrekt service ved tilstedeværelsen af forskellige fejl, der skyldes tekniske problemer i forbindelse med bestemmelse af køretøjets lokalitet. Hovedformålet med fejl-tolerant design inden for afgiftsprocessen er at sikre retfærdig taksering af brugerne. Det betyder, at redundante systemer, procedurer og komponenter bør indføres for at sikre, at når fejl og svigt forekommer inden for afgiftsprocessen vil kørselsafgiftsfundamentet stadig være pålideligt og give retfærdige resultater for både brugerne og kørselsafgiftssystemet. Denne afhandling konkluderer derfor, at selv om performanceniveauet for bestemmelsen af køretøjets lokalitet er fair, bør opmærksomheden omkring systemets performance rettes imod hvordan fremtidige GNSS-baserede kørselsafgiftssystemer kan designes til at virke driftsikkert med forekomsten af både data invaliditet og datamangler. Det er derfor vigtigt at udvide fokus fra tekniske udfordringer og komponentunøjagtigheder alene til et fokus på pålideligheden af systemet som helhed. Der er dog stadig nogle teknologiske udfordringer at overvinde, som i højere grad elimineres ved bedre samarbejde på tværs af de mange forskellige involverede fagområder. Som med mange andre ITS-systemer, kan vellykket design, implementering og drift af et system kun opnås, når de mange forskellige interessenter forstår hinandens krav til systemet. Systemarkitekturen som konceptuelt design sammen med den systemteoretiske metode kan bidrage til at

involvere alle de forskellige parter i systemudviklingen og dermed minimere de misforståelser, der i sidste ende kan blive meget dyre for systemet.

Baseret på de mange resultater af dette ph.d.-studie, er nogle generelle retningslinjer endeligt formuleret for fremtidige GNSS-baserede kørselsafgifts-systemer. De foreslåede retningslinjer, der er beskrevet i afhandlingen omfatter både GNSS-baserede kørselsafgiftsforsøg i almindelighed og et fremtidigt GNSS-baserede kørselsafgiftssystem i Danmark.



---

*"Dancing in all its forms cannot be excluded from the curriculum of all noble education; dancing with the feet, with ideas, with words, and, need I add that one must also be able to dance with the pen."*

*Friedrich Nietzsche (1844-1900)*



# Preface

---

This thesis is the result of a PhD study entitled "GNSS-based Road Charging Systems – Assessment of Vehicle Location Determination". The study is sponsored by Siemens and has been prepared at the Department of Transport, Technical University of Denmark. The PhD study has been supervised by Professor Otto Anker Nielsen.

This PhD study deals with assessing the performance of the vehicle location determination that computes the position measurements used for road charging. The study is based on a technical road charging experiment conducted as a part of this PhD work in collaboration with Siemens during 2007–2009. The work presented in this thesis is relevant for authorities, companies and researchers working with GNSS-based road charging systems. However, the methodologies, results and considerations presented can also be applied for other GNSS-based liability-critical applications.

This thesis is submitted as a partial fulfillment of the requirements for the degree Doctor of Philosophy PhD in engineering science.

Kgs. Lyngby, Denmark,  
May 2011

Martina Zabic



# Acknowledgments

---

First and foremost I would like to express my gratitude to my supervisor Professor Otto Anker Nielsen for introducing me to the subject of satellite-based road charging systems many years ago and supervising my PhD study. My former co-supervisor René Munk Jørgensen is also thanked for his help during the initiating phases of the project. Thanks to their understanding, I attended various technical meetings, seminars, conferences and courses, which have provided a significant contribution to the quality of the research presented in this thesis.

Siemens is sincerely acknowledged for sponsoring the study financially and providing technology and technical support for the road charging experiment. I would like to express my gratitude to all those who were involved in the different phases of the road charging experiment, especially to Christoph Wondracek from Siemens Industrial Solutions & Services Department: Electronic Toll Solutions in Austria and Mettemarie Tange from Siemens Power Transportation Department in Denmark for their dedication and practical support during the experiment. TDC Mobile is acknowledged for providing GPRS communication for data transmission during the experiment and Peter Linnemann from dk Mobil Center is thanked for installation and de-installation of on-board technology in all the vehicles.

I am very grateful for the many people who accepted to participate in the experiment and for letting me install road charging technology in their vehicles. Without them, the valuable input for my PhD work would not have been the same and I sincerely appreciate their participation and patience throughout the project. Center for Parking, Copenhagen and the taxi drivers are acknowledged for participating with several vehicles in the experiment.

During my PhD study, I was fortunate to visit the Imperial College Engineering Geomatics Group (ICEGC) at Centre for Transport Studies, Imperial College London from October 2008 – March 2009. During my stay, I met many interesting and highly skilled researchers whose research and enthusiasms have been a great inspiration for my PhD work. However, my biggest gratitude goes to Professor Washington Y. Ochieng, who has played an important role in the inspiration, supervision, and achievement of excellence in my research. A heartfelt gratitude goes to Marie-Dominique Dupuy and Amado Crotte for the wonderful friendship they offered me and for making my stay in London one of my best experiences. The Idella Foundation and the Reinholdt W. Jorck og Hustrus Foundation are acknowledged for financially supporting my visit at Imperial College London.

I would also like to thank my colleagues and fellow research students at the Department for Transport, Technical University of Denmark for their comments, good discussions and continuous support during my PhD study. Special thanks go to Kenneth Christensen and Allan Olsen for supporting my lack of programming skills; to Sara L. Jeppesen and Alex Landex for commenting on specific chapters; to Hanne L. Petersen for her Latex support; and to Christian Würtz for his help with map-matching and his patience with my never-ending questions regarding the AKTA project.

I wish to thank my family and friends for their support and patience during especially the last part of the PhD work. A special thank goes to my dearest friend Anne Sophie for her eternal support and interest in my work during the years of my PhD study; and to the rest of the girls for always reminding me of the joy of

dancing. A heartfelt gratitude goes to my dear Kristian for his constant support through the ups and downs of this challenging journey, for coping with my long study hours, and for his confidence in me. Last but certainly not least, my deepest appreciation goes to my parents. I am grateful for their endless and loving support throughout my education, for teaching me that nothing is impossible and for always believing in me.

*My sincerest gratitude,  
Martina*





# Contents

---

|  |             |
|--|-------------|
| <b>Abstract</b>                                    | <b>i</b>    |
| <b>Resumé</b>                                      | <b>vii</b>  |
| <b>Preface</b>                                     | <b>xv</b>   |
| <b>Acknowledgments</b>                             | <b>xvii</b> |
| <b>1 Introduction</b>                              | <b>1</b>    |
| 1.1 Background . . . . .                           | 1           |
| 1.2 Research Questions and Objectives . . . . .    | 3           |
| 1.3 Outline of the Thesis . . . . .                | 3           |
| 1.4 Main Contributions of this PhD Study . . . . . | 6           |
| <b>2 The Potential of Road Charging Systems</b>    | <b>9</b>    |
| 2.1 Introduction . . . . .                         | 9           |
| 2.2 Urban Congestion Problems . . . . .            | 11          |
| 2.3 Charging for Road Use . . . . .                | 18          |

|          |  |            |
|----------|--|------------|
| 2.4      | Summary . . . . .                                      | 45         |
| <b>3</b> | <b>System Fundamentals</b>                             | <b>47</b>  |
| 3.1      | Introduction . . . . .                                 | 48         |
| 3.2      | System Engineering Methodology . . . . .               | 50         |
| 3.3      | Conceptual Design . . . . .                            | 57         |
| 3.4      | High-Level Functional Architecture . . . . .           | 67         |
| 3.5      | Summary . . . . .                                      | 79         |
| <b>4</b> | <b>Performance Requirements</b>                        | <b>81</b>  |
| 4.1      | Dependability . . . . .                                | 82         |
| 4.2      | Road Charging Process . . . . .                        | 84         |
| 4.3      | Navigation Function . . . . .                          | 86         |
| 4.4      | Charging Function . . . . .                            | 96         |
| 4.5      | Literature review of GNSS-based Case Studies . . . . . | 101        |
| 4.6      | Summary . . . . .                                      | 127        |
| <b>5</b> | <b>Technical Road Charging Experiment</b>              | <b>131</b> |
| 5.1      | Background . . . . .                                   | 131        |
| 5.2      | Experimental design . . . . .                          | 135        |
| 5.3      | Technical Challenges . . . . .                         | 136        |
| 5.4      | Other Challenges . . . . .                             | 139        |
| 5.5      | Data Reliability Assessment . . . . .                  | 141        |
| 5.6      | Summary . . . . .                                      | 160        |
| <b>6</b> | <b>Performance Assessment of VLD</b>                   | <b>163</b> |
| 6.1      | Satellite Availability in Copenhagen . . . . .         | 164        |
| 6.2      | Assessment of RNP . . . . .                            | 174        |

|                   |  |            |
|-------------------|--|------------|
| 6.3               | Time To First Fix . . . . .                              | 196        |
| 6.4               | Discussions on VLD Performance . . . . .                 | 210        |
| 6.5               | Summary . . . . .  | 214        |
| <b>7</b>          | <b>Gap Influence on Driven Distance Determination</b>    | <b>217</b> |
| 7.1               | Gap Influence on Driven Distance Determination .         | 217        |
| 7.2               | TTFF Influence on Distance Determination . . . .         | 231        |
| 7.3               | Gap Influence Results . . . . .                          | 237        |
| 7.4               | Discussions on Gap Influence . . . . .                   | 241        |
| 7.5               | Summary . . . . .  | 243        |
| <b>8</b>          | <b>Dependability of GNSS-based Road Charging Systems</b> | <b>245</b> |
| 8.1               | Dependability Risk Assessment . . . . .                  | 246        |
| 8.2               | Fault Tolerant Road Charging Systems . . . . .           | 253        |
| 8.3               | Proposed Guidelines . . . . .                            | 257        |
| 8.4               | Final thoughts... . . . .                                | 259        |
| <b>9</b>          | <b>Conclusions</b>                                       | <b>263</b> |
| 9.1               | Conclusions . . . . .                                    | 263        |
| 9.2               | Main Contributions of this Work . . . . .                | 267        |
| 9.3               | Recommendations for Future Research . . . . .            | 268        |
| <b>Appendices</b> |  |            |
| <b>A</b>          | <b>Haversine Formula</b>                                 | <b>1</b>   |
| A.1               | Determination of Distance Between Two Points . .         | 1          |



# List of Figures

---

|      |  |    |
|------|--|----|
| 1.1  | PhD Thesis Structure. . . . .                                | 5  |
| 2.1  | Total Number of Passenger Cars in EU-27. . . . .             | 12 |
| 2.2  | Open Toll System. . . . .                                    | 30 |
| 3.1  | System Life Cycle. . . . .                                   | 51 |
| 3.2  | The Vee Development Model . . . . .                          | 55 |
| 3.3  | Prime Entities in a Road Charging System. . . . .            | 58 |
| 3.4  | Classification of Road Charging System Requirements. . . . . | 59 |
| 3.5  | Decomposition of System Functions. . . . .                   | 67 |
| 3.6  | System Management Functionalities. . . . .                   | 69 |
| 3.7  | User Service Management Functionalities. . . . .             | 70 |
| 3.8  | Vehicle Location Determination Functionalities. . . . .      | 72 |
| 3.9  | Charge Construction Functionalities. . . . .                 | 73 |
| 3.10 | Enforcement & Inspection Functionalities. . . . .            | 74 |
| 3.11 | Billing Management Functionalities. . . . .                  | 76 |

|   |     |
|---|-----|
| 3.12 High-Level Functional System Architecture. . . . .   | 77  |
| 4.1 Functional Flowchart of the Road Charging Process. . . . .  | 85  |
| 4.2 Cumulative Charging Methods. . . . .  | 98  |
| 4.3 Cumulative Charging Possibilities. . . . .  | 100 |
| 5.1 Experiment Timescale. . . . .   | 132 |
| 5.2 Experiment Set-up. . . . .  | 133 |
| 5.3 Performance Assessment Analyses Presented in this Thesis. . . . .   | 134 |
| 5.4 Example of Invalid Trip with Zero Mileage. . . . .  | 143 |
| 5.5 Cumulative Frequency of Trip Durations. . . . .   | 144 |
| 5.6 Cumulative Frequency of Trip Durations for Copenhagen based on the Danish National Travel Survey. . . . . | 144 |
| 5.7 Distribution of Trip Mileage. . . . .   | 145 |
| 5.8 Examples of Overlapping Trips. . . . .  | 146 |
| 5.9 Trip A1. . . . .  | 147 |
| 5.10 Overlapping Trips per OBU in Percent of Total Number of Trips. . . . .                                   | 148 |
| 5.11 Gaps Occurrences per OBU. . . . .  | 150 |
| 5.12 Distribution of Gap Durations. . . . .   | 150 |
| 5.13 Gap Durations as Percent of Total Time Travelled. . . . .  | 151 |
| 5.14 Cumulative Frequency of Gap Durations less than 1 Minute. . . . .  | 152 |
| 5.15 Total Number of Gap Occurrences per Trip. . . . .  | 153 |
| 5.16 Gap Duration Sums per Trip. . . . .  | 153 |
| 5.17 Gap Duration per Vehicle. . . . .  | 154 |
| 5.18 Gaps $\leq 10$ seconds. . . . .  | 155 |

|   |     |
|---|-----|
| 5.19 Gaps $\geq 11$ and $\leq 300$ seconds. . . . .   | 156 |
| 5.20 Gaps $> 5$ min and $< 1$ hour. . . . .   | 157 |
| 5.21 Gaps $> 1$ hour. . . . .   | 158 |
| 6.1 Distribution of Visible Satellites in 2003 and 2008. . . . .                              | 165 |
| 6.2 Mean Values and Percentiles for 2003 and 2008 . . . . .                                   | 166 |
| 6.3 Optional caption for list of figures . . . . .  | 168 |
| 6.4 Optional caption for list of figures . . . . .  | 169 |
| 6.5 Distribution of HDOP in 2003 and 2008. . . . .  | 170 |
| 6.6 Optional caption for list of figures . . . . .  | 172 |
| 6.7 Optional caption for list of figures . . . . .  | 173 |
| 6.8 Coverage of 1,000 Trips and Gaps. . . . .   | 176 |
| 6.9 Satellite Availability as Percent of Total Time Trav-<br>elled. . . . .                   | 177 |
| 6.10 Positioning Ratio. . . . .   | 178 |
| 6.11 Cumulative Frequency of Satellite Availability dur-<br>ing Total Time Travelled. . . . . | 180 |
| 6.12 Fix Densities for 5 m and 100 m Accuracy Levels. . . . .                                 | 183 |
| 6.13 Proximity Analysis Examples. . . . .   | 184 |
| 6.14 Gaps per Trip. . . . .   | 185 |
| 6.15 Gap Duration Ratio. . . . .  | 186 |
| 6.16 Distribution of Maximum Gap Duration per Trip. . . . .                                   | 187 |
| 6.17 Spatial Distribution of Gap Durations. . . . .   | 189 |
| 6.18 Distribution of Gap Distances. . . . .   | 190 |
| 6.19 Gap Distance Ratio. . . . .  | 191 |
| 6.20 Distribution of Maximum Continuous Gap Distances. . . . .                                | 191 |
| 6.21 Spatial Distribution of Gap Distances. . . . .   | 193 |

|      |   |     |
|------|---|-----|
| 6.22 | Time To First Fix. . . . .  | 199 |
| 6.23 | Distribution of Time Between Trips. . . . .   | 200 |
| 6.24 | Time To First Fix compared to Time Between Trips.   | 201 |
| 6.25 | Distribution of TTFF Gap Durations within Startup<br>Categories. . . . .                      | 202 |
| 6.26 | Cumulative Frequency of TTFF Gaps within Startup<br>Categories. . . . .                       | 202 |
| 6.27 | Distribution of Distance To First Fix. . . . .  | 204 |
| 6.28 | Time To First Fix Compared to Distance to First<br>Fix. . . . .                               | 205 |
| 6.29 | Distribution of Distance To First Fix within Differ-<br>ent Startup Categories. . . . .       | 205 |
| 6.30 | Cumulative Frequency of Distance To First Fix within<br>different Startup Categories. . . . . | 206 |
| 6.31 | Average Gap Distances for Time To First Fix Du-<br>rations. . . . .                           | 207 |
| 6.32 | Spatial Distribution of Time To First Fix. . . . .  | 208 |
| 6.33 | Spatial Distribution of Time To First Fix Distances.  | 209 |
| 6.34 | Gap Classification in Percent of Total Time Travelled.  | 211 |
| 6.35 | Distribution of Gap Classes within the Percentage<br>of Trips. . . . .                        | 212 |
| 7.1  | Optional caption for list of figures . . . . .  | 221 |
| 7.2  | Event Tree for Distance-based Charging. . . . .   | 239 |
| 7.3  | Event Tree for Distance-related Charging. . . . .   | 240 |
| 8.1  | Dependability Risk Matrix for the VLD Function.   | 251 |



# List of Tables

---

|     |  |     |
|-----|--|-----|
| 1.1 | Main Contributions of this PhD Thesis. . . . .   | 8   |
| 2.1 | Overview of Different Road Charging Schemes. . .   | 36  |
| 2.2 | Enabling Technologies for Collecting, Transmitting<br>and Processing Data in Road Charging Schemes . | 39  |
| 3.1 | Functional Building Blocks of GNSS-based Road<br>Charging Systems. . . . .                           | 66  |
| 4.1 | Error Source and Their Potential Error Size. . . .   | 93  |
| 4.2 | RNP for Liability-Critical Road Applications. . . .  | 94  |
| 4.3 | Accuracy Comparison of the Seven Devices. . . . .  | 104 |
| 4.4 | Results of GPS Accuracy Assessment. . . . .  | 108 |
| 4.5 | Results of GPS Accuracy Assessment. . . . .  | 110 |
| 4.6 | Main Results From MapFlow Analyses of TfL's GPS<br>Data. . . . .                                     | 113 |
| 4.7 | Overview of Map-matching Performance. . . . .  | 115 |
| 4.8 | Lateral GPS-position Accuracies per Road Class. .  | 117 |

|      |  |     |
|------|--|-----|
| 4.9  | Comparison of GPS and Odometer Distances. . . .                                      | 118 |
| 4.10 | Calculated GPS Deviations in Meter per Kilometer<br>per Road Category. . . . .       | 119 |
| 4.11 | Accuracy of the Calculated Distance. . . . .   | 121 |
| 4.12 | Mean and standard deviations . . . . .   | 124 |
| 4.13 | Summary of Results - Part 1. . . . .   | 128 |
| 4.14 | Summary of Results - Part 2. . . . .   | 129 |
| 5.1  | Data Characteristics. . . . .  | 135 |
| 5.2  | Receiver Specifications. . . . .   | 136 |
| 5.3  | Examples of Overlapping Trips. . . . .   | 146 |
| 5.4  | Frequency of Different Error Types in Data. . . .                                    | 160 |
| 6.1  | Data Characteristics for the Subset. . . . .   | 175 |
| 6.2  | Fix Densities within Accuracy Levels. . . . .  | 181 |
| 6.3  | Time To First Fix Scenarios. . . . .   | 203 |
| 6.4  | Rating Chart of the VLD Performance . . . . .  | 213 |
| 7.1  | Gap Types. . . . .   | 218 |
| 7.2  | Simulation Scenarios. . . . .  | 219 |
| 7.3  | Determined Distances for Different Scenarios of Distance-<br>based Charging. . . . . | 222 |
| 7.4  | Frequency of Distance Deviations in Distance-based<br>Charging. . . . .              | 223 |
| 7.5  | Distance Deviations in Percent of OBU Mileage. .                                     | 224 |
| 7.6  | Distance Determination Results for Distance-related<br>Charging. . . . .             | 226 |
| 7.7  | Frequency of Distance Deviations in Distance-related<br>Charging. . . . .            | 227 |

---

|      |  |     |
|------|--|-----|
| 7.8  | TTFF Intervals . . . . .   | 231 |
| 7.9  | TTFF Simulation Scenarios. . . . .                                       | 232 |
| 7.10 | Distance Determination Results for Distance-based<br>Charging. . . . .   | 233 |
| 7.11 | Distance Determination Results for Distance-related<br>Charging. . . . . | 235 |
| 8.1  | Summary of Distance Determination Performance.                           | 252 |
| 8.2  | Guidelines for GNSS-based Road Charging Trials.                          | 258 |
| 8.3  | Guidelines for GNSS-based Road Charging in Den-<br>mark. . . . .         | 260 |



# Acronyms

---

|                |  |
|----------------|--|
| <b>2D</b>      | Two Dimensional                                  |
| <b>3D</b>      | Three Dimensional                                |
| <b>3G</b>      | 3rd Generation Mobile Telecommunications         |
| <b>AOA</b>     | Angle of Arrival                                 |
| <b>ABS</b>     | Anti-lock Braking System                         |
| <b>ADAS</b>    | Assisted Driver Assistance System                |
| <b>A-GPS</b>   | Assisted Global Positioning System               |
| <b>ANPR</b>    | Automatic Number Plate Recognition               |
| <b>ATC</b>     | Air Traffic Control                              |
| <b>CPD</b>     | Carrier Phase Differential                       |
| <b>COO</b>     | Cell of Origin                                   |
| <b>DBMS</b>    | Data Base Management Systems                     |
| <b>DOP</b>     | Dilution of Precision                            |
| <b>DR</b>      | Dead Reckoning                                   |
| <b>DSRC</b>    | Dedicated Short Range Communication              |
| <b>DTFF</b>    | Distance-To-First-Fix                            |
| <b>EGNOS</b>   | European Geostationary Navigation Overlay System |
| <b>ETA</b>     | Event Tree Analysis                              |
| <b>ETC</b>     | Electronic Toll Collection                       |
| <b>EU</b>      | European Union                                   |
| <b>GDP</b>     | Gross Domestic Product                           |
| <b>GIS</b>     | Geographic Information System                    |
| <b>GLONASS</b> | GLobal Orbiting NAvigation Satellite System      |

|                |   |
|----------------|---|
| <b>GNSS</b>    | Global Navigation Satellite System              |
| <b>GPRS</b>    | General Packet Radio Service                    |
| <b>GPS</b>     | Global Positioning System                       |
| <b>GSM</b>     | Global System for Mobile communications         |
| <b>HDOP</b>    | Horizontal Dilution of Precision                |
| <b>HGV</b>     | Heavy Goods Vehicle                             |
| <b>HSGPS</b>   | High Sensitivity Global Positioning System      |
| <b>INS</b>     | Inertial Navigation System                      |
| <b>IT</b>      | Information Technology                          |
| <b>ITS</b>     | Intelligent Transport Systems                   |
| <b>LAN</b>     | Local Area Network                              |
| <b>NAVSTAR</b> | NAVigation by Satellite Timing And Ranging      |
| <b>MEMS</b>    | Micro Electro Mechanical System                 |
| <b>OBU</b>     | On Board Unit                                   |
| <b>RAIM</b>    | Receiver Autonomous Integrity Monitoring        |
| <b>RFID</b>    | Radio Frequency Identification                  |
| <b>RNP</b>     | Required Navigation Performance                 |
| <b>SMS</b>     | Short Message Service                           |
| <b>SoS</b>     | Systems-of-Systems                              |
| <b>TBT</b>     | Time Between Trips                              |
| <b>TOA</b>     | Time of Arrival                                 |
| <b>TDOA</b>    | Time Difference of Arrival                      |
| <b>TDM</b>     | Transport Demand Management                     |
| <b>TDP</b>     | Time-Distance-Place                             |
| <b>TTF</b>     | Time-To-First-Fix                               |
| <b>UK</b>      | United Kingdom                                  |
| <b>USERE</b>   | User Equivalent Range Error                     |
| <b>US</b>      | United States                                   |
| <b>VAS</b>     | Value Added Service                             |
| <b>VLD</b>     | Vehicle Location Determination                  |
| <b>WAAS</b>    | Wide Area Augmentation System                   |
| <b>WAN</b>     | Wide Area Network                               |
| <b>WiFi</b>    | Wireless Fidelity                               |
| <b>WiMAX</b>   | Worldwide Interoperability for Microwave Access |

# Introduction

---

## 1.1 Background

There is an increasing demand for satellite-based road charging systems in Europe. Within recent years, governments and decision makers have become aware of the possibility of reducing the urban transport problems in Europe by the use of satellite systems. Several countries are hence considering initiating a national-scale satellite-based road charging system.

In Denmark, the Government is considering implementing a satellite-based road charging system as road charging and toll ring systems have been discussed intensively in Copenhagen during the last 10 years. As a part of the green transport policy, decided in 2009, the Danish Government wish to implement an intelligent kilometer-based road charging system at a national scale in Denmark [[Ministry of Transport, 2008](#)]. The objective hereof is that it should be cheaper to buy a new, safe and environmentally friendly car, but more expensive to drive the car - especially in congested periods and areas [[Næss-Schmidt et al., 2010](#)]. How-

ever, the timescale for implementing intelligent road charging in Denmark is at the time of writing undefined.

Satellite-based road charging involves charging road users for their road usage by allowing the vehicles to locate themselves within a certain charge area using Global Navigation Satellite Systems (GNSS). GNSS-based road charging systems allow for cumulative distance charging, where charges are calculated for each individual vehicle based on the distance driven, the time of the trip and the vehicles' geographic position. Hence GNSS-based road charging systems are considered a more fair and efficient way of charging as these schemes levy charge proportionally to the distance travelled, and thereby reflect a usage-based approach more accurately than other charging policies. GNSS-based systems have the advantage that they more easily can be modified and expanded for larger geographic coverage or new areas and that they also are able to provide value added information and services to the drivers such as real time weather and traffic information. In the light of these benefits, policy makers are looking at initiating nationwide GNSS-based congestion charging schemes. However, nationwide road charging on the basis of the distance travelled is technically challenging and is seen as one of the most complex schemes.

GNSS-based road charging systems are considered liability-critical systems, where denial of service and undetected faults and failures generate significant legal or economic negative consequences. As many other ITS applications, GNSS-based road charging systems use various technologies (computers, communications, sensors etc.) and include a continuous exchange of information within the system. In GNSS-based road charging systems the computed position, velocity and/or time are used as the basis for charging [Cosmen-Schortmann et al., 2008]. Any fault or failures that lead to incorrect charging may cause economic loss or provoke wrong legal decisions as the economic liability is associated to the legal aspects due to the repercussion of potential claims. Dependability is hence an important requirement for a GNSS-based road charging system as the system must provide fair charging and gain user trust by ensuring system reliability and liability.



## 1.2 Research Questions and Objectives

This PhD study deals with assessing the performance of the vehicle location determination function that computes the position measurements used for charging. Therefore the focus of this thesis is framed by the two following research questions:

- What is the existing performance level of the vehicle location determination with state of the art road charging technology?
- What are the technological challenges of the vehicle location determination in GNSS-based road charging systems?

The aim of this thesis is hence to provide an overall assessment of the challenges and performance level of the vehicle positioning in GNSS-based road charging systems. Based on a technical road charging experiment conducted in Copenhagen as a part of this PhD work, this thesis aims at providing results on the present level of performance of GNSS-based road charging systems. To do so, the objectives of this PhD thesis are:

- To provide an overview of existing road charging schemes and enabling technologies.
- To understand the functional and non-functional requirements for GNSS-based road charging systems and define a conceptual design.
- To provide new methodologies for performance assessment of the vehicle location determination function.
- To suggest guidelines for future GNSS-based road charging systems.

## 1.3 Outline of the Thesis

The PhD thesis consists of nine chapters, structured so as to reflect the research objectives listed above. Each chapter consists

of different sections and subsections, beginning with a short introduction and ending with some concluding remarks. The overall thesis structure is given in Figure 1.1. The organisation of the thesis is as follows:

**Chapter 1** introduces the PhD study and defines the **purpose** and outline of the thesis. This includes an outline of the key research questions and main objectives; and a outline of the thesis content.

**Chapter 2** describes the **potential of road charging systems**. The chapter introduces the road transport problems and describes the different road charging objectives, followed by a classification of the many different types of charging schemes. An overview of existing road charging schemes is provided together with a description of enabling technologies for road charging schemes.

**Chapter 3** defines the **conceptual framework** based on the concepts of system engineering. The chapter classifies the system requirements and determines the functional requirements for the satellite-based charging systems. This is followed by a description of the different system functionalities and a definition of the high-level system architecture for GNSS-based road charging systems.

**Chapter 4** presents the overall **performance requirements** for satellite-based road charging systems. The chapter highlights the road charging process as the key part of a road charging system and defines a functional flowchart for this process. A description of the navigation function and the charge calculation methods is provided, followed by an in-depth literature review of GNSS-based road charging studies.

**Chapter 5** presents the **technical road charging experiment** conducted as a part of the PhD study. This includes the experimental design and the challenges during the experiment. Hereafter, a data reliability assessment is presented together with the main results of this assessment.

|                   | Chapter   | Title  | Main features  |
|-------------------|-----------|--|--|
| Setting the Scene | Chapter 1 | Introduction   | <ul style="list-style-type: none"> <li>• Background</li> <li>• Research questions and objectives</li> <li>• Outline of the thesis</li> </ul>   |
|                   | Chapter 2 | The Potential of Road Charging Systems                   | <ul style="list-style-type: none"> <li>• Description of charging objectives</li> <li>• Classification of road charging systems</li> <li>• Overview of existing charging schemes</li> <li>• Description of enabling technologies</li> </ul> |
|                   | Chapter 3 | System Fundamentals                                      | <ul style="list-style-type: none"> <li>• Classification of system requirements</li> <li>• Determination of functional requirements</li> <li>• Description of conceptual design</li> <li>• Definition of high-level architecture</li> </ul> |
|                   | Chapter 4 | Performance Requirements                                 | <ul style="list-style-type: none"> <li>• Definition of functional road charging process flow-chart</li> <li>• Specification of overall performance requirements</li> <li>• Literature review of GNSS-based studies</li> </ul>              |
| Experiment        | Chapter 5 | Technical Road Charging Experiment in Copenhagen         | <ul style="list-style-type: none"> <li>• Main experiment</li> <li>• Determination of technical challenges</li> <li>• Assessment of data reliability</li> </ul>   |
|                   | Chapter 6 | Performance Assessment of Vehicle Location Determination | <ul style="list-style-type: none"> <li>• Assessment of satellite availability</li> <li>• Assessment of required navigation performance</li> <li>• Time-To-First-Fix assessment</li> </ul>  |
|                   | Chapter 7 | Gap Influence on Driven Distance Determination           | <ul style="list-style-type: none"> <li>• Simulation methodology</li> <li>• Gap influence assessment</li> </ul>   |
| Findings          | Chapter 8 | Dependability of GNSS-based Road Charging Systems        | <ul style="list-style-type: none"> <li>• Dependability risk assessment</li> <li>• Fault tolerant road charging systems</li> <li>• Proposed guidelines</li> <li>• Discussions</li> </ul>  |
|                   | Chapter 9 | Conclusions  | <ul style="list-style-type: none"> <li>• Main contributions</li> <li>• Conclusions</li> <li>• Recommendations for future research</li> </ul>   |

Figure 1.1: PhD Thesis Structure.

**Chapter 6** provides the **main performance assessments** of the vehicle location determination function. First, a comparative assessment of the satellite visibility and dilution of precision in Copenhagen between 2003–2008 is presented. This is followed by an assessment of the required navigation performance parameters and the time to first fix based on new methodologies developed for this research. Finally, a thorough discussion of the assessment results is presented together with a classification of the error contributions to the vehicle location determination function.

**Chapter 7** presents an assessment of the **positioning gap influence** on the driven distance determination based on new simulation methodologies developed for this purpose. The gap influence results are summarized for both charging methodologies and the probabilities of different charging outcomes are demonstrated.

**Chapter 8** discuss the **dependability of GNSS-based road charging** systems. The results from these different assessments in this thesis are summarized and the dependability risk is assessed. Hereafter, this chapter discusses fault tolerant road charging system design and provides the guidelines proposed by this thesis for both GNSS-based trials and future road charging systems.

**Chapter 9** presents the **findings and main contributions** of this PhD thesis. This is followed by the thesis conclusions and recommendations for future research.

## 1.4 Main Contributions of this PhD Study

This PhD study deals with assessing the performance of the vehicle location determination function that computes the position measurements used for charging. In the process of answering the stated research question, this PhD work has contributed with:

- A **theoretical study** on GNSS-based road charging systems contributing with a thorough description of the potential of

GNSS-based road charging systems, the functional and performance requirements to the core system functions, the system architecture and a comprehensive overview of existing road charging schemes and previous performance studies.

- A **technical road charging experiment** contributing with new results on the GNSS-based road charging system performance based on state of the art OBU technology. The experiment, including 40 vehicles, was conducted in Copenhagen between 2007 and 2008. Siemens provided the road charging technology while the overall management, coordination and evaluation of the experiment was conducted within this PhD study.
- A **comprehensive assessment** of the vehicle location determination performance based on both the collected data from the experiment and simulation. The assessment contributes with new performance assessment methodologies, comparisons with previous research and new results and dependability conclusions.

The main contributions of the PhD thesis are given in Table 1.1.

Additionally, the technical road charging experiment with Siemens has contributed with great new experiences on trial set-up and execution regarding GNSS-based road charging systems. Through good cooperation with Siemens, the technical challenges regarding this experiment have given both parties valuable knowledge about improving technical solutions and more importantly knowledge about the next steps forward towards future intelligent road charging systems.

| Main contributions  | Described in:    |
|---|------------------|
| <ul style="list-style-type: none"> <li>An overview and classification of existing road charging schemes and enabling road charging technologies.</li> </ul>   | Chapter 2        |
| <ul style="list-style-type: none"> <li>An identification of the functional and non-functional requirements for GNSS-based road charging systems.</li> </ul>   | Chapters 3, 4    |
| <ul style="list-style-type: none"> <li>A definition of the conceptual design of GNSS-based road charging systems; together with a description of system functionalities and a definition of the high-level functional architecture.</li> </ul>                                  | Chapter 3        |
| <ul style="list-style-type: none"> <li>A description and definition of a functional flowchart for the road charging process within GNSS-based road charging systems.</li> </ul>   | Chapter 4        |
| <ul style="list-style-type: none"> <li>An in-depth literature review of GNSS-based case studies regarding road charging.</li> </ul>   | Chapter 4        |
| <ul style="list-style-type: none"> <li>New results on vehicle location determination performance based on a technical GNSS-based road charging experiment; together with a classification of the error contributions.</li> </ul>  | Chapters 5, 6, 7 |
| <ul style="list-style-type: none"> <li>A methodology for assessing the data reliability prior to exclusion of invalid data records.</li> </ul>  | Chapter 5        |
| <ul style="list-style-type: none"> <li>A comparative assessment of the satellite visibility and dilution of precision in Copenhagen between 2003--2008 based on a GIS methodology developed by this thesis.</li> </ul>  | Chapter 6        |
| <ul style="list-style-type: none"> <li>An assessment of the required navigation performance for liability-critical road transport applications; including new methodologies developed by this thesis for assessing the positioning continuity and time to first fix.</li> </ul> | Chapter 6        |
| <ul style="list-style-type: none"> <li>An assessment of the gap influence on the driven distance determination based on a new simulation methodology developed for this research.</li> </ul>  | Chapter 7        |
| <ul style="list-style-type: none"> <li>A probability assessment based on the results from this thesis of the different charging outcomes for both distance-based and distance-related charging.</li> </ul>  | Chapter 7        |
| <ul style="list-style-type: none"> <li>A dependability risk assessment of the different challenges and failures.</li> </ul>   | Chapter 8        |
| <ul style="list-style-type: none"> <li>Proposed guidelines for fault tolerant road charging design; and for future GNSS-based road charging trials and -systems.</li> </ul>   | Chapter 8        |

**Table 1.1:** Main Contributions of this PhD Thesis.

## CHAPTER 2

# The Potential of Road Charging Systems

---

The aim of this chapter is to describe the potential of road charging systems. The chapter introduces the urban transport problems and describes the causes of congestion. Next, the different road charging objectives are described, followed by a classification of the many different types of charging schemes. Finally, an overview of existing road charging schemes is provided together with a description of enabling technologies for road charging schemes.

## 2.1 Introduction

Close to 495 million citizens live in Europe<sup>1</sup> and most of them use transport in their everyday-life. As transport provides these citizens with access to goods, services, employment and social activities, it also creates an ever-increasing need for sustainable mobility.

European cities increasingly face problems caused by traffic and

---

<sup>1</sup>EU 27 [European Commission, 2008]

transport as the growing need for mobility meets the restrictions of limited road space. Most transport problems occur whenever the transport demand exceeds the infrastructure supply, resulting in congestion. However, expanding the road network to increase the infrastructure supply is not a realistic approach towards sustainable mobility, as studies indicate that in time new mobility demands will meet up with the road capacity levels again ([Noland, 2002] provides a comprehensive review).

Satellite based road or congestion charging is one way of ensuring that travel demand is distributed more evenly across available road space and time of day and several strategies exist on how to implement these systems [Pickford and Blythe, 2006]. Hence there is an increasing demand for satellite based road charging systems in Europe. Within recent years, governments and decision makers have become aware of reducing the urban transport problems in Europe by the use of satellite systems and several countries, are considering national scale satellite-based road charging systems. Satellite-based road charging involves charging road users for their road usage by allowing the vehicles to locate themselves within a certain charge area using Global Navigation Satellite Systems (GNSS).

Road charging systems may take a number of different forms. Depending on the charging objective, these road charging systems can be designed in various forms and varied by both policy and technology but they all share the overall function of charging vehicle users for their road usage. As many other intelligent transport systems, road charging systems use a wide range of various technologies (computers, communications, sensors etc.) and include several different elements that need to interact successfully in order to obtain an effective road charging system.

The aim of this chapter is to create a basis for the research on GNSS-based road charging systems presented in this thesis. The chapter firstly describes the congestion problems in Europe and the means by which road charging can help to reduce congestion and its environmental impacts. Secondly, the chapter defines eight different road charging schemes and provides a comprehen-



sive overview of existing road charging schemes and the technologies enabling these schemes.

## 2.2 Urban Congestion Problems

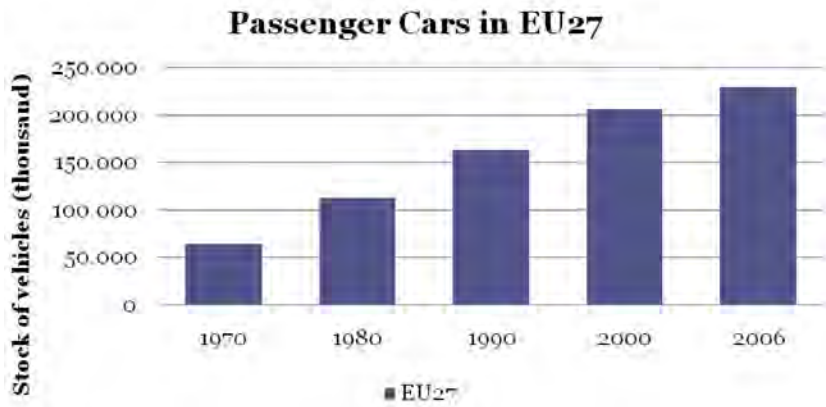
Over the past several decades, the demand for transport in Europe has increased dramatically, causing urban areas across Europe to suffer from persistent and rising transport problems.

Since 1980, the number of passenger cars in Europe has doubled (see Figure 2.1, [European Commission, 2007]) and in addition, goods vehicles have increased by more than 40 % since 1995. Between 1980 and 2006, car ownership grew from 238 to 466 cars per 1,000 inhabitants in the EU27 and in the recent decade from 1996 to 2006 the passenger transport<sup>2</sup> (measured in billion passenger kilometres) raised by 15.6 % [ERF, 2008]. The largest share of intra-EU transport is carried by road, which accounts for 44 % of freight and around 85 % of passenger transport. According to the European Commission, the overall distance travelled by road vehicles has tripled within the last 30 years [European Commission, 2008]. Forecasts suggest that, without any action, traffic will continue to grow considerably over the next decade, adding 35 % more passenger vehicles and 50 % freight transport to the European roads by 2020 [De Ceuster et al., 2005].

The growth in traffic implies a number of serious consequences that impacts the society in different ways. The increasing traffic causes congested roads in urban areas, which result in huge economic losses for society, merely due to wasted time and lost productivity. Furthermore, traffic consumes energy and generates environmental impacts as air pollution, noise and severance effects. These impacts threaten city environments across Europe and are growing contributors to the world's climate changes, but above all these environmental impacts they also affect the health of the urban population. Safety, stress and accidents are also related to the increased congested traffic as it corresponds with the growing

---

<sup>2</sup>EU 27



**Figure 2.1:** Total Number of Passenger Cars in EU-27.

number of accidents and fatalities, primarily due to the combination of high vehicle densities and the stress caused by congested driving conditions. The question of how to enhance mobility while at the same time reducing congestion and its consequences is a common challenge to all major cities in Europe.

### 2.2.1 The Congestion Problem

Road congestion is the most common transport problem in urban areas across Europe [European Commission, 2008]. As the traffic levels climbed during the 1970s, 80s and 90s, the infrastructure was not able to keep up with this growth resulting in today's high level of congestion which the Europeans must tolerate every day.

Road congestion is generally known as a condition where the traffic demand exceeds the roadway capacity which is often characterized by slower speeds, longer trip times, delays and increased queuing. A more sophisticated definition was formulated in 2004 by Professor of Transport Policy, Philip Goodwin:

*"Congestion is defined as the impedance vehicles impose on each other, due to the speed-flow relationship, in conditions where the use of a transport system approaches its capacity."* [Goodwin, 2004]

Congestion can principally be categorized into two types: recurrent and non-recurrent congestion. Recurrent congestion is the result of factors that cause regular demand in the transport network such as mandatory home-work trips, shopping or weekend travels and hereby reflects the morning and afternoon peak periods. Non-recurrent congestion is caused by random events such as unexpected incidents and unusual weather conditions, such as vehicles breakdowns, special events, accidents, road construction work and bad weather conditions [European Conference of Ministers of Transport, 2007].

### 2.2.2 Causes of Congestion

The increase in traffic congestion in European cities is the result of both economic trends affecting demand for road usage, and policy trends that have constrained the network supply.

Within the latest decades, several factors have influenced the growth of the total vehicle fleet, particularly in the fast-growing countries of central Europe. One key factor underlying this strong growth in demand is the shifts in demographics toward urban areas resulting in an increased urban population. In 2008, one half of the world's population are living in urban areas and the proportion is still increasing. According to United Nations [UN, 2006] the world's urban population is projected to increase to 4.9 billion people by 2030, nearly 60 % of humankind. In comparison, the world's rural population is expected to decrease by some 28 million between 2005 and 2030, indicating that at a global level, all future population growth is expected to be in towns and cities. In Europe<sup>3</sup>, the Commission of European Communities [European Commission, 2008] estimated that 80 % of the European population is living in urban areas in 2007. The outcome of the urbanization is a change in the socio-economic development as urbanization involves new forms of employment, economic activity and lifestyle which jointly increase the mobility in cities and promote the use of private vehicles. Economic growth has also contributed with rising

---

<sup>3</sup>EU 25

personal incomes, stimulating an increased car usage in central Europe and resulting in a higher level of car ownership. Furthermore, the economic development has also increased the growth of goods transport within the EU, at a rate of 2.8 % per year [European Commission, 2008].

Inadequate supply of road infrastructure capacity for the growing level of demand is another key factor towards congestion. In Europe, the road infrastructure and capacity has been extended throughout the last decades to provide better accessibility between cities, but the growth of urban transport demand occurred at a higher rate than expected. In addition, the attempt to mitigate congestion by providing new roadway capacity has in most cases shown an opposite effect, where the supply of new infrastructure capacity only provided a short-run congestion relief and instead lead to changes in travel patterns resulting in additional travels and a return to the original or even higher congestion level [European Conference of Ministers of Transport, 2007].

The combination of increasing road usage and limitations in the road infrastructure has unavoidably led to increased traffic, resulting in the congestion level that most Europeans must bear today.

### 2.2.3 Congestion Impacts

The growth in traffic has other serious consequences causing worsened environmental conditions at both local and global levels, and increasing the strains on energy resources. Road transport is without doubt a leading factor in economic development as economic opportunities are likely to arise where transportation infrastructures are able to answer mobility needs and insure access to markets and resources. However, road vehicle usage imposes various costs and consists of both internal costs borne by the road user and external costs that the vehicle imposes on other road users and the society as a whole. These costs can either be fixed (e.g. vehicle ownership) or variable (e.g. fuel costs) in proportion to the vehicle usage. An overview of the transport cost categories linked to vehicle usage can be found in [Litman, 1999].

Traffic congestion costs are those external impacts which an additional vehicle imposes on other road vehicle users in the form of reduced speeds. Each vehicle on a congested road system both imposes and bears congestion costs, but the impacts are not evident until the traffic volume exceeds a particular level [Kveiborg, 2001]. The congestion costs consist of increased delays, vehicle costs, accident risk and stress that are imposed on other road vehicle users, but congestion also imposes external costs (e.g. delays) to other transport modes such as cyclists and public transport. Inequitable, these other transport modes must bear the same congestion delay costs as the single occupant vehicle users [Victoria Transport Policy Institute, 2009]. In general, vehicle users are only concerned with the internal cost they must bear themselves such as fuel costs, repair and maintenance and their own travel time costs. As a result, they tend to underestimate the external (social) cost of their trips as for instance air pollution, noise, health threats and congestion affecting other travellers and the society.

Several cost estimations and analyses exist in the literature ([Jakob et al., 2006], [Litman, 2009]) and especially the costs of transport externalities have been brought into focus ([Maibach et al., 2008], [Delucchi, 1997]) as the increasing number of vehicle users are not accounted for their external costs. The unpaid social costs of the increasing transport have resulted in a liability to society which can be considered from economic, social and environmental dimensions.

### 2.2.3.1 Economic impacts

As traffic grows, congestion becomes more widespread and also the occurrence increases from peak hour congestion to congestion during most of the day. As a consequence, road traffic in the European cities is moving more slowly than ever with an average traffic speed of only 15km/h [European Commission, 2003]. In 2006, the European Commission estimated that 7,500 kilometres of European roads on a daily basis are blocked by traffic jams, contributing to a total cost of road congestion in EU of approximately

125 billion Euros per year or 1 % of the EU's GDP in terms of lost productivity due to wasted time, while at the same time leading to fuel wastage, increased air pollution and reduced public transit efficiency [European Commission, 2006].

Furthermore, road traffic congestion impose significant operating expenses to businesses in particular those associated with freight and service deliveries. Delays in time-sensitive deliveries can impose additional costs to businesses within their inventory, logistic, reliability or just-in-time production, costing the businesses billions of dollars in lost productivity and exports.

### 2.2.3.2 Environmental impacts

The growing road usage in Europe is strongly linked to increasing environmental problems at both a local and global level. The most important environmental impacts are related to climate changes, air quality and noise besides the high level of energy consumption.

Road transport is by far the biggest transport emission source accountable for 93 % of total transport emissions [EEA, 2007]. Between 1990 and 2005, transport caused the largest increase in greenhouse gas emissions with 26 % due to the high growth in both passenger and freight transport. In 2005, greenhouse gas emissions from transport accounted for 21 % of the total EU-15 emissions, mostly due to carbon dioxide (CO<sub>2</sub>) from fuel combustion. According to the European Commission, urban transport is responsible for around 40 % of total road transport carbon dioxide emissions and nearly all of Europe's urban inhabitants are exposed to air pollution levels that exceed EU limits for particulate matter (PM) [European Commission, 2007]. It has been estimated that the transport environmental costs account for around 100 billion Euros.

The emission of CO<sub>2</sub> from vehicles is directly linked to the fuel consumption and as travel time increases in congested conditions, the fuel consumption and hence CO<sub>2</sub> emission increases in addition. It is generally admitted that pollutant emissions are dependent on the speed levels, and measurements have shown that the highest

rates of emission occur in congested, slow moving traffic [André and Hammarström, 2000]. Emission rates are much higher in conditions with numerous re-accelerations (stop-and-go conditions), than those when vehicles are driven more smoothly. Furthermore, there is a tendency for emission rates to increase at high speeds, especially NO<sub>x</sub> [DfT, 2006].

### 2.2.3.3 Social impacts

Noise emissions are a more obvious impact coming from the transport sector. Road noise is generated by four main sources: vehicles, friction between vehicles and the road surface, driver behaviour plus construction and maintenance activity (see [Tsunokawa and Hoban, 1997] for a review). The impacts of road noise are greatest where busy roads pass through densely populated areas where the sound level corresponds to a level of 65 to 90 dB.

According to the European Federation for Transport and Environment, around 50,000 people in the EU die prematurely each year from heart attacks caused by traffic noise [European Commission, 1996]. According to the European Environment Agency [EEA, 2001], approximately 120 million people in the EU (more than 30 % of the total population) are exposed to road traffic noise levels above 55 dB and more than 50 million people are exposed to noise levels above 65 dB. The total costs to society of traffic noise emissions in the EU including cost to health services, are estimated to at least 40 billions per year (or 0.4 % of total GDP) of which about 90 % are caused by passenger cars and goods vehicles [T&E, 2001].

In addition to the indirect health impact from noise and air pollution, transport activity is responsible for serious injuries and death through traffic accidents. In urban areas, congestion impacts on road safety and increases the risk of accidents due to high vehicle densities combined with the stress caused by congested driving conditions. The risk of traffic accidents depends on the traffic flow and the degree of congestion, but also on the type of vehicle, road conditions and driver behaviour. Furthermore, it has been argued

that the number of accidents in urban areas rises more than proportionally for high levels of traffic [European Commission, 1999]. According to the European Commission, about 42,000 people are killed on European roads every year, an average of 115 people every day. The direct costs of vehicle accidents are estimated to cost 45 billion Euros annually [European Commission, 2003].

The above-mentioned costs and impacts of congestion highlight the continual challenges for the transport sector in Europe as well as other industrialized parts of the world. With the increasing awareness of a more environmentally sustainable development, the transport sector has to face requirements of increasing the transport system capacity and improving mobility while reducing the unpaid external costs of transport affecting people throughout the world.

## 2.3 Charging for Road Use

Road congestion in urban areas continues to increase as a consequence of higher mobility demands. Due to the high costs of land acquisition and construction of new roads, the supply side of the transport infrastructure remains unchanged, which at the end results in continuous congestion problems. Various solutions to tackle road congestion have been proposed worldwide. With respect to reducing congestion, these solutions can be classified into two overall categories:

- increasing the supply of road space and capacity to meet the mobility demand (supply-side strategies)
- managing down the demand to fit within the available road infrastructure supply (demand-side strategies)

For a review of supply and demand-side strategies refer to [Faiz et al., 1990], [Alvarado, 2008] and [Meyer et al., 1989].

Supply side strategies are used with the intent of meeting the current demand immediately by increasing the supply of road capacity. However, it is generally argued that improvements in the



supply side alone, will be unable to meet the demand for travel, and that some means of controlling the demand are also needed [May, 1992]. The expansion of roads is limited in older cities and may even cause growth in traffic volumes, which eventually leads to higher levels of congestion. Furthermore, it has been argued that supply side solutions like increasing road capacity only provides short-run congestion relief before induced travel demand causes traffic congestion to return to its original level again (refer to [Noland and Lem, 2002] for a thorough review).

Demand-side strategies are designed to reduce the impact of traffic by influencing peoples travel behavior and better balance peoples need to travel a particular route at a particular time with the capacity of available facilities. The focus of demand-side strategies is to provide people with enhanced travel choices including choices in travel mode, departure-time and route choices and to provide incentives and information for people to make informed travel choices. Demand-side strategies can focus on short-term actions designed to mitigate existing congestion problems, or on more strategic approaches to avoid future congestion [Meyer et al., 1989]. There is a wide range of measures within travel demand management (TDM), ranging from simple traffic control, provision of facilities and services to encourage alternative transport modes, to incentives to discourage travel and reduce driving (see [Loukopoulos, 2007] for an overview).

These TDM measures can be classified into four categories [Gärling and Schuitema, 2007]:

- Physical changes measures – which aim at making alternative travel modes more attractive. It involves improving public transport and infrastructure for walking and cycling to encourage alternative travel modes and land use planning to encourage shorter travel times.
- Legal policies – implemented to enforce vehicle use. Examples include prohibiting vehicle traffic in city centers, decreasing speed limits, and introducing parking regulations.
- Economic policies – which aim at making vehicle use rela-

tively more expensive to discourage driving. This included road charging strategies, of fuels and cars, and reducing costs for public transport.

- Information and education measures –which aim at changing people’s perceptions and behavior concerning vehicle use. It involves providing information about benefits and disbenefits of vehicle use, the environmental consequences of congestion and information about alternative travel modes.

Refer to [[Victoria Transport Policy Institute, 2009](#)] for a comprehensive review of transport demand management (TDM) strategies.

Within recent years, governments and decision makers have become aware of reducing the urban transport problems in Europe by use of road charging strategies. Road charging has become accepted as an appropriate policy tool for reducing transport problems as it changes travel behaviour and discourages driving [[Jaensirisak, 2003](#)]. By implementing road charging, vehicle owners are encouraged to change their habits by travelling at different times or by different routes, possibly to alternative destinations, or making their journey by public transport and other alternative transport modes. The great interest in road charging is due to its potential to cope with the growth of travel demand and to generate revenue for transport projects.

### 2.3.1 Charging Objectives

The underlying principle for road charging is that road users should be directly charged for the additional costs which their use of road space imposes on the rest of society. The main cost is that of congestion (the delay the drivers cause to others), but in principle the environmental costs of noise, risk and pollution, social costs and the road costs of construction and maintenance could be taken into account as well. The arguments for this principle dates back to [[Pigou, 1920](#)], [[Knight, 1924](#)] and [[Vickrey, 1963](#)]. Their inspiration was to charge road users a fee equal to the total

cost of their trip. They argued that by imposing a toll-tax on a congested road, total travel time would be reduced and encourage the more efficient use of road space, so that society's welfare would be enhanced [Rouwendal and Verhoef, 2006]. According to the economic theory, the objective of the road charging policy is to make users more aware of the costs that they impose upon each other when driving during the peak periods, and that they should pay for the additional congestion they create by use of the price mechanism. This encourages the redistribution of the transport demand or shifts it to a substitute, for example public transport. The economic theoretical foundations behind road charging are described in detail in [Hau, 1992] and [Rouwendal and Verhoef, 2006].

The objectives and applications of road charging have evolved since from a purely economic concept to an urban management policy aiming principally to reduce congestion and mitigate the negative environmental impacts, while generating revenue for other policies [Sumalee et al., 2009]. There are essentially two approaches, which are not necessarily mutually exclusive for implementing road charging for the use of roads [Eliasson and Lundberg, 2002]:

- Generate revenue for financing road investments
- Manage traffic congestion and internalising external costs

Tolling or toll collection are terms used, when applying road charging to finance infrastructure such as new roads, tunnels or bridges. The objective of toll systems is to raise the necessary revenue to meet the financial targets by setting a toll-level that will not encourage too many road users from selecting alternative routes. The toll is typically levied to recover the investment, operations and maintenance costs for that infrastructure. When implementing road charging for transport management purposes, the objective is to reduce congestion and mitigate the negative environmental impacts, by setting a charge level that will encourage road users not to travel by vehicle in the road network. This is known as road use charging or congestion charging [Pickford and Blythe, 2006]. Furthermore, road charging systems can be designed combining revenue generation with travel demand and congestion manage-

ment in order to raise revenue that may be put back into improving transport infrastructure, supporting public transport, and generally offering alternatives to travel by private vehicle [Tsekeris and Voß, 2009].

Different cities will have differing objectives for the implementation of road charging. The EU-funded CURACAO project [CURACAO, 2008] conducted a survey of a number of cities across Europe, and found the fundamental objectives of road charging to be as follows:

- Congestion relief
- Environmental protection
- Equity and social inclusion
- Generating revenues for transport investments

In addition, other objectives for road charging systems include the following: protecting economic growth, health, liveability, safety, and protecting the needs of future generations. The survey also demonstrated that most cities pursue a combination of objectives. While initiated road charging systems may have multiple goals, the objective considered most important usually determines the type of road charging scheme selected [Eliasson and Lundberg, 2002].

### 2.3.2 Types of Road Charging

These differences in charging objectives lead to differences in system design and in performance. Depending on the desired objectives and the local policies, road charging schemes can take in various forms. During the last decades, the development in road charging schemes have gone from simple manual toll systems implemented in local corridors, to complex nationwide systems based on automated vehicle tracking technologies, where charges may be varied according to time, distance and location, and furthermore diverged after vehicle characteristics including weight, size and emissions.

Due to the many variations in charging schemes and the ongoing development in road charging technology, different classifica-

tions of road charging schemes exist ([Gomez-Ibanez and Small, 1994], [Pickford and Blythe, 2006] , [Sorensen and Taylor, 2006] and [Road User Charging Interest Group, 2007]). The classification of road charging schemes used in this thesis is developed based on the classification proposed by the GNSS Metering Association for Road User Charging [GMAR, 2010]. It defines eight different basic types of road charging schemes, grouped into two overall classes: discrete and continuous charging schemes [Grush et al., 2009]. The eight types of road charging schemes are given in the following:

### Discrete Road Charging Schemes

In discrete charging schemes, charges are based on the detection of distinct events.

**Single Event Charging** involves charging of distinct single events such as passing a bridge, tunnel or mountain pass. In single object charging schemes, vehicles are charged per passage at a specific point. The toll is levied on vehicles passing through the toll plaza. The toll is generally a fixed charge but may vary by time of day. Most tolled bridges, such as the Øresund Bridge between Denmark and Sweden, belong to this category and can include both manual and automated toll facilities.

**Closed Road Charging** involves charging in closed road networks. In closed road charging schemes, all exit and entry points are monitored and tolls are collected on exit, so that the toll paid is in proportion to the length of the used section. The charge depends on where the network was entered and exited and a fixed charge is applied for the driven distance between the entry and exit. With a closed road charging system, the vehicles typically collect a ticket when entering the motorway and pay the required toll on exit. This can either be manually at toll plazas or electronically using vehicle tracking technologies and wireless communication. The

closed road charging scheme is the most common form for motorway tolling in Europe<sup>4</sup> as for instance in Croatia [Pribanic et al., 2006], where most of the highways use closed toll collection systems.

**Open Road Link Charging** involves charging for driving on specific segments of roads, whether or not used in their entirety. Open road link charging typically has no toll plazas on entry or exit ramps to the roads. The charges are collected at points along the road by use of vehicle tracking systems and wireless communications, which identifies the route travelled on the specified toll road segments. The charges are determined based on the length of each road segment (distance-related) rather than true distance measurements (distance-based). The open road link charging schemes are for instance implemented in the German HGV tolling system and in the Austrian GO-Maut electronic tolling system for heavy goods vehicles.

**Cordon Cross Charging** involves vehicles are being charged as they cross a particular boundary line often, to a heavily congested area such as a city core. The primary objective of cordon cross charging schemes is to reduce the number of vehicles entering. Every entry point is equipped with means of identifying vehicles, which can either be manual toll booths or automated vehicle tracking technologies as microwave DSRC technology or automatic number plate recognition systems (ANPR). Cordon charging is distinct from zone charging in that vehicles already within the cordon are not charged, and that vehicles crossing the boundary more than once are charged per crossing. The charge is typically a fixed charge for crossing the cordon but may be varied by time of day or have a maximum payment per day or month. According to [Pickford and Blythe, 2006], cordon cross charging is the most common charging scheme for urban demand management. The cordon cross charging schemes are for in-

---

<sup>4</sup>Belgium, France, Ireland, Italy, Norway, Portugal, Spain, Turkey and UK

stance implemented in several cities in Norway and also for the Stockholm congestion charging.

**Zone Presence Charging** involves charging triggered by using a vehicle inside a zone regardless of whether its boundary is crossed or not. The zone presence charging scheme is a variant of the cordon cross charging in which the charge is levied for using a vehicle within the defined area, rather than just to enter it. The charges may be varied by time of day, type of vehicle or level of congestion. The zone presence charging scheme is for instance applied in Singapore and also used for the London congestion charging system.

### Continuous Road Charging Schemes

In continuous charging schemes, charges are determined using accumulated time, distance or other cumulated parameters.

**Cumulative Distance Charging** involves charging on the basis of the distance travelled (as measure of usage). In cumulative distance charging schemes also known as distance-based charging, the charge is levied as an amount per distance driven, i.e. per kilometre and therefore requires independent distance readings. These distance readings are typically performed by sensor technologies such as odometers, digital tachographs and GNSS or as a combination hereof. In cumulative distance charging schemes, the charges may furthermore be varied by vehicle characteristics or time of day. The cumulative distance charging scheme is applied for the Swiss HGVs charging system.

**Spatial Cumulative Distance Charging** involves charging on the basis of the distance travelled with different tariffs applied according to spatial characteristics such as specified zone(s) or road type(s). The spatial cumulative distance charging schemes are also known as time-distance-place (TDP) charging and is under consideration by many European coun-

tries. Time-distance-place charging schemes require independent distance readings for determination of the driven distance throughout the specified zones in order to accommodate a variable charge dependent upon time-distance-place. The charge may also vary according to the driving direction. Today, no spatial cumulative distance charging schemes exist.

**Time-in-use Charging** involves charging according to the accumulated time a vehicle has been in operation, alternatively by the time the vehicle has been present inside a specified zone. Time-based charging requires independent time readings for determination of the time the vehicle has been in use. These time readings are typically performed by a combination of clock and sensor technologies measuring the ignition and movement of the vehicle. The time-in-use charging scheme is applied for the Eurovignette system in the following countries: Belgium, Denmark, Luxembourg, the Netherlands and Sweden.

Each of these eight types of charging schemes can, in addition, be varied by modifying the charges based on vehicle characteristics such as trailer presence, and by day of week, such that charges are higher in rush hours and lower on the weekends. Variable charges can be applied based on a pre-set schedule which is updated periodically or dynamically in response to real-time changes in demand. According to economists, variable or dynamic road charging is the best way of overcoming congestion problems.

### 2.3.3 Existing Road Charging Schemes

There have been many implementations and trials of road charging across the world. In this section, selected road charging schemes are explained as examples according to the definitions given above.



### 2.3.3.1 Single Event Charging

Single event charging schemes are implemented many places in the world, as most tolled bridges and toll roads belong to this category. Although most of them operate with manual fee collection, many also offer automated electronic toll facilities. Single event charging schemes have become increasingly common for this type of tolling, as it can help in reducing local traffic congestion (directional), and raise revenue for operations and maintenance costs.

In Norway, several toll bridges and tunnels exits, which use single event charging to finance the operations and maintenance costs. In most cases, payment can be made at manual toll stations by traditional means (cash, credit cards, etc) or by the electronic fee collection system AutoPASS . The AutoPASS system ([www.autopass.no](http://www.autopass.no)), requires an OBU which works as an electronic tag, to be fixed on the windscreen of the vehicle. The tag's ID is connected to the vehicle's registration number, and can be read at the toll stations either at the entrance or exit of a tunnel, road or bridge. There are three types of toll plazas with the AutoPASS system:

- Manned toll service stations with coin machines and manned booths
- Unmanned toll stations with card and coin machine
- Automatic AutoPASS stations, where stop-and-pay it is not possible

Vehicles passing without the AutoPASS tag, will have a picture taken of the car's registration number and an invoice is sent to the owner of the car free of charge. Toll roads without AutoPASS have coin machines, or manual booths for payment.

In UK, the M6 Toll Motorway ([www.m6toll.co.uk](http://www.m6toll.co.uk)) uses a single event charging scheme to reduce congestion. All vehicles using the M6, must pass through one toll plaza, either at one of two main toll stations at the M6 motorway, or at one of the eight exit junctions along the road. The M6 toll system automatically classifies vehicles by use of sensors that measures the number of axles and the vehicle height. The charges depend on the classification of the

vehicle and alter according to time of day and day of week. Payments can be made at either a manned lane booth (cash, coins and cards), or at an automatic booth, using cards or coins only.

Similarly, single point charging schemes exist in many other European countries, such as France (Frejus and Mont Blanc Tunnel), Ireland (M1, M4 and East-Link Toll Bridge), Belgium (Liefkenshoek Tunnel), Netherlands (Kiltunnel) and UK (M48 Severn Bridge). The Golden Gate Bridge in San Francisco, US, is a well-known example of a toll bridge.

The 23 km stretch of the A14 motorway between the German border and Hohenems in Austria and further into Switzerland, also uses a new type of single event road charging scheme called a Korridor-Vignette. All vehicles up to 3.5 tonnes using the motorway stretch, must buy a vignette (valid for 24 hours) to use this route without having to purchase a full toll sticker. The Korridor-Vignette is valid for a one-way trip.

### **2.3.3.2 Closed Road Charging**

Closed road charging schemes are the most common form for motorway tolling in Europe, often used as an instrument of the financing and management of roads. The closed road charging schemes are typically implemented for motorway tolling with monitored entry and exit points along the road.

In Italy, a closed road charging scheme is used for the motorway network Autostrade per l'Italia ([www.autostrade.it](http://www.autostrade.it)). The toll charge is measured by registering when and where the vehicles enters and exits the toll road network. The charge amount depends on the route length and is usually determined by means of a ticket issued at the motorway access. Payment can be in cash, credit card or with the electronic Telepass systems. Telepass can be used for all types of vehicles which can travel on Italian motorways. Telepass consists of an On-Board Unit (OBU) mounted at the top of the vehicle's windscreen, which works as an electronic tag. The tag's ID is connected to the vehicle's registration number, and can be read at the toll stations at the entrances and exits of the

Autostrade motorway network.

In Croatia, most of the highways use a closed toll collection systems [Pribanic et al., 2006]. At entry stations, two-module self-service ticket issuers are installed. The lower level for personal vehicles and the upper level for heavy goods vehicles. In the Croatian closed toll collection system ([www.hac.hr](http://www.hac.hr)), two modes of operation exist:

- A manual mode, where the driver presses a button that issues a ticket followed by an automatic opening of the barrier
- An automatic mode, where tickets are issued automatically at either the upper or lower level, detected by optical height sensors followed by a automatic opening of the barrier

If the system detects and OBU or a SMARTcard in the vehicle, the data which would be recorded onto the ticket (magnetic stripe card) are instead recorded on the OBU or SMARTcard. At each entry station, video cameras furthermore records licence plates of vehicles. At exit stations, a cashier takes the tickets obtained at entrance and the toll charge is calculated according to the point of entrance and the vehicle class. For vehicles with OBU or SMARTcard, the transaction is performed automatically.

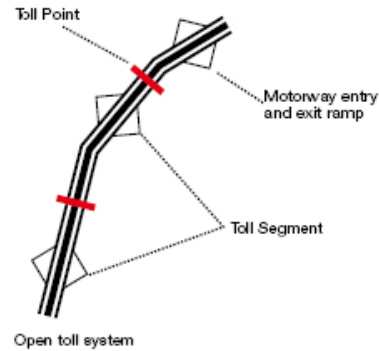
Other similar closed road charging schemes are found in France, Serbia, Spain, and Ohio and Florida in the US.

### 2.3.3.3 Open Road Link Charging

Open road link charging involves charging for driving on specific segments of roads. Open road link charging schemes are typically implemented with no toll plazas on entry or exit ramps to the road and the toll charges are instead collected at points along the road.

The Austrian GO-Maut electronic tolling system for heavy goods vehicles is an open road charging scheme designed to finance operations and maintenance of motorways in Austria ([www.go-maut.at](http://www.go-maut.at)). The system includes six Austrian special toll sections, which are subject to separate tariffs. All vehicles with a maximum admissible

weight of more than 3.5t are subject to pay toll. The GO-maut system is a multi lane free flow system, which allows vehicles to travel without stops at the toll segments. It is characterized by gantries placed above the motorway lanes, using microwave transceivers mounted on the gantries to communicate with OBUs installed on the windscreen of passing vehicles. Each section and direction needs one portal with one gantry for toll communication in each sector between the exit/entry-points on the motorways (refer to Figure 2.2 [Kapsch Trafficcom]). The charge is determined based on the length of the road segments and is thereby in proportion to the distance driven [Schwarz-Herda, 2005]. For the A13 Brenner motorway section, the toll charges are furthermore varied according to time of day. In the GO-maut system, payment can be effected in advance with toll credits that can be purchased in cash, with credit or petrol card (pre-pay) or by a centrally registered account (post-pay).



**Figure 2.2:** Open Toll System.

The German HGV tolling system ([www.toll-collect.de](http://www.toll-collect.de)) is a more complex open road link charging scheme designed to implement direct user fees, raise revenues and institute an emission-based toll [Toll Collect, 2007]. The German HGV system is an automatic toll collection system for heavy goods vehicles (more than 12t) based on GPS, a microwave transmitter and virtual toll plazas. The vehicles are equipped with an OBU which through the use

of GPS, internal sensors and on board cartographic data, identifies the route travelled on the toll motorways [Wieland, 2005]. All motorways are divided into road segments, whose geographical co-ordinates are stored in the OBUs. The system uses GPS to ascertain what segments the vehicle has travelled on, with a digital tachograph for secondary back-up measurements. The charge is determined based on the length of each road segment (to give a consistent result) rather than true distance measurements Matheson [2005]. The OBU calculates the corresponding amount of toll charge and sends these data via the microwave transmitter to the system's central data processing unit, which manages the billing. The German system is considered the technologically most ambitious system in Europe [Wieland, 2005].

Other similar open road link charging schemes are found in the French TIS-PL (partly), the Italian Telepass (partly), the Czech Nationwide Truck e-Toll System (MYTO CZ) and in the Slovakian SkyToll system.

#### 2.3.3.4 Cordon Cross Charging

Cordon cross charging involves charging vehicles when they cross a particular boundary line of a specified area with the primary objective of reducing the number of vehicles entering the area. Cordon cross charging schemes are the most common charging scheme for urban demand management [Pickford and Blythe, 2006].

In Norway, seven cordon cross charging schemes (toll rings) exist which reduce congestion and help to finance the operations and maintenance costs of the roads and support the public transport infrastructure investments in Norway [Ieromonachoua et al., 2006]. The first Norwegian toll ring was implemented in Bergen in 1986, and since then other Norwegian cities have adopted the cordon cross charging scheme including: Oslo, Trondheim, Stavanger and Kristiansand (see [AECOM Consult, 2006] for a detailed review). Oslo uses an automatic toll collection system called AutoPASS (www.autopass.no). The electronic fee collection is carried out by using an OBU which identifies every vehicle during movement

into the charging area at a defined boundary point. There are 19 operating toll stations located in a ring around the city of Oslo. At every entry point a signal, sent by radar equipment placed in these gates, detects the AutoPass electronic tag (OBU) mounted on the windshield of passing vehicles and deducts the appropriate charge from a pre-paid account. Non-users of the electronic system can pass without AutoPass as the vehicle's numberplate is registered by ANPR and an invoice is sent to the vehicle owner subsequently. In the Norwegian cordon cross charging schemes, the toll charges are fixed charges varied by vehicle classes.

In Stockholm, a cordon cross charging scheme ([www.vv.se](http://www.vv.se)) covers a 30 km<sup>2</sup> area of central Stockholm with the main objective to reduce congestion during morning and afternoon peak periods [Alvarado, 2008]. The charging scheme in Stockholm is similar to the toll rings in Norway. At each entry station, vehicles are identified by video cameras with automatic number plate recognition (ANPR) software, which sends a decoded numberplate string and photos in real-time to a central server. There are no payment options at the toll ring entry, all payments in the Stockholm charging system are pre- or post-pay. Unlike the Norwegian toll rings, the toll charges are varied according to time of day and have a maximum daily charge. Refer to [Kalauskas et al., 2009] for a more detailed review of the Stockholm charging system.

Other similar cordon cross charging schemes are found in Warsaw in Poland, Bologna in Italy, and Riga in Latvia.

#### 2.3.3.5 Zone Presence Charging

The zone presence charging scheme is a variant of the cordon cross charging in which the charge is levied for using a vehicle within the defined area, rather than just to enter it. The charges may be varied by time of day, type of vehicle or level of congestion.

Singapore was a pioneer in zone presence charging [Cottingham et al., 2007]. The first zone presence road charging scheme, known as the Area Licensing Scheme (ALS), was introduced in the Restricted Zone (RZ) of Singapore in 1975 in an attempt to control

the traffic levels within the city ([www.lta.gov.sg](http://www.lta.gov.sg)). Vehicles were required to display a paper-based license to drive within the restricted zone. Since then, the system has developed and today, Singapore uses an electronic cordon cross charging scheme called the Electronic Road Pricing (ERP) system. The current ERP system is designed to control congestion based on a desired travel speed on the designated roads and expressways. The ERP system uses dedicated short-range radio communication (DSRC) to deduct toll charges from OBUs with pre-paid CashCards mounted on the windshield of vehicles driving in the zone. The charges are levied on a per-pass basis and are varied according to type of vehicle, day of the week, time of day and the traffic conditions at the charging points. Every three months the fees are revised based on whether the travel speeds are above or below the desired speed. The changes in fees are advertised through electronic signs at each collection point.

London implemented a zone presence charging scheme known as the London Congestion Charging (CC London) in 2003 to reduce congestion and the environmental impacts. In the London charging scheme ([www.cclondon.com](http://www.cclondon.com)), vehicles are charged a fixed daily rate (£8) to travel into or within Central London on weekdays from 7am - 6pm. Charges can either be pre-paid or paid the day of travel in the cordon area either by telephone, in shops or online. The vehicles do not have on board electronic tags. Instead, the system is entirely reliant on a network of roadside automatic number plate recognition cameras (ANPR), which photograph vehicle number plates and check them against a database to work out whether the vehicle has paid. The roadside cameras are located at entry points and are also present within the zone to record vehicles that remain within it. In the London zone presence charging scheme, residents of the charging area receive a 90 % discount.

#### 2.3.3.6 Cumulative Distance Charging

Cumulative distance charging schemes also known as distance-based charging, involves charging on the basis of the distance trav-

elled (as measure of usage) which therefore requires independent distance readings.

In 2001, Switzerland implemented an electronic cumulative distance charging scheme for heavy goods vehicles ([www.ezv.admin.ch](http://www.ezv.admin.ch)). All vehicles exceeding 3.5 tons are levied a charge (LSVA) that is proportional to the distance driven on all public roads and varied according to vehicle characteristics (weight and emissions). The vehicles use complex OBUs consisting of GPS, DSRC, a movement sensor and a digital tachograph [Balmer, 2003]. The tachograph measures the distance (kilometres) travelled as the primary measurement device. A GPS sensor and a movement sensor provide a second, redundant measurement in order to verify the tachograph measurements. The DSRC is used for automatic detection of border crossings. [Rapp and Balmer, 2004] provide a comprehensive review of the Swiss charging scheme.

In cumulative distance charging schemes, the charges may furthermore be varied by time of day.

#### 2.3.3.7 Spatial Cumulative Distance Charging

Spatial cumulative distance charging schemes involve charging on the basis of the distance travelled with different tariffs applied according to spatial characteristics such as specified zone(s) or road type(s). The spatial cumulative distance charging schemes are also known as time-distance-place (TDP) charging and is under consideration by many European countries.

The Netherlands, was the first country to initiate national time-distance-place charging to all vehicle classes on all public roads. The objective was to reduce congestion, introduce fair charges and raise revenue earmarked for transport investments [International Transport Forum, 2006]. The Dutch Government initiated a spatial cumulative distance charging scheme known as Kilometer Pricing (KMP) which later was cancelled. The KMP system was to include the full road network of approximate 130,000 km and involve 8 millions Dutch registered vehicles ([www.verkeerenwaterstaat.nl](http://www.verkeerenwaterstaat.nl)). The system was planned as a GNSS-based system and was to be



introduced for heavy goods vehicles by 2011 and for all vehicles by 2018. No design details were decided, but an automatic charging system, which calculates the charge for each individual vehicle based on the distance driven, the time of the trip and the vehicles geographic position (zone, road type or direction) was planned [T-Systems Satellic, 2006]. The charges were furthermore planned to be varied according to vehicle characteristics such as vehicle class and emissions.

To the author's knowledge no other spatial cumulative distance charging schemes exist at the time of writing.

#### 2.3.3.8 Time-in-use Charging

Time-in-use charging involves charging according to the accumulated time a vehicle has been in operation, alternatively by the time the vehicle has been present inside a specified area.

The Eurovignette is a time-in-use charging scheme for heavy goods vehicles which currently exists in Belgium, the Netherlands, Luxembourg, Denmark and Sweden ([www.eurovignette.eu](http://www.eurovignette.eu)). All heavy goods vehicle over 12 tonnes must buy a Eurovignette paper licence to use motorways in any of these five countries. The licence, which give access to use the motorways for a specified amount of time (day, week, month or year), can be purchased at petrol stations, service areas near motorway access roads and online. The Eurovignette charge is varied according to vehicle characteristics (emissions and number of axles). The Eurovignette is enforced via spot checks and penalties are linked to the time spent travelling on the motorways without the licence [HM Treasury, 2002].

All the explained examples from this section are summarized in Table 2.1.

### 2.3.4 Enabling Technologies

The first official acknowledgement of the technical possibilities of the direct charging at the point of use was the Smeed Report

| Charging Type               | Country   | Scheme                           | Vehicles             | Network                                       | Parameters  | Technology                           | References          |
|-----------------------------|---|----------------------------------|----------------------|---|---|--------------------------------------|---------------------|
| Single Event                | Norway  | AutoPass                         | All classes          | Roads<br>Tunnels<br>Bridges                   | Vehicle class   | DSRC                                 | www.autopass.no     |
|                             | UK  | M6 Toll<br>Motorway              | All classes          | Motorway                                      | Axles<br>Time of day/week                             | DSRC<br>Sensors                      | www.m6toll.co.uk    |
| Closed Road                 | Italy   | TelePass                         | All classes          | Motorways                                     | Route length<br>Vehicle class                         | DSRC                                 | www.autostrade.it   |
|                             | Croatia   | HAC                              | All classes          | Motorways                                     | Road length<br>Vehicle class                          | DSRC<br>Smart Card<br>Sensors        | www.hac.hr          |
| Open Road Link              | Austria   | G-O-Maut                         | HGVs >3.5t           | Motorways                                     | Link length<br>Emissions<br>Axles                     | DSRC                                 | www.go-maut.at      |
|                             | Slovakia  | SkyToll                          | HGVs >3.5t<br>Busses | Motorways<br>Expressways<br>First-class roads | Time of day/week<br>Link length<br>Axles<br>Emissions | GPS<br>DSRC                          | www.skytoll.sk      |
|                             | Czech   | MYTO CZ                          | HGVs >3.5t           | Motorways<br>Expressways                      | Link length<br>Axles<br>Emissions<br>Time of day/week | DSRC                                 | www.myto.cz         |
|                             | Germany   | Toll Collect                     | HGVs >12t            | Motorways<br>Trunk roads                      | Link length<br>Weight<br>Emissions                    | GPS<br>DSRC<br>Sensors<br>Tachograph | www.toll-collect.de |
|                             | Norway  | Bergen<br>Oslo<br>Trondheim      | All classes          | Cordon  | Entry/Exit  | DSRC                                 | www.autopass.no     |
| Zone Presence               | Sweden  | Stockholm                        | All classes          | Cordon  | Entry/Exit<br>Time of day<br>Vehicle class            | ANPR                                 | www.vv.se           |
|                             | UK  | London<br>Congestion<br>Charging | All classes          | In zone                                       | Vehicle class   | ANPR                                 | www.cclondon.com    |
| Cumulative Distance         | Switzerland   | LSVA                             | HGVs > 3.5t          | All roads                                     | Weight<br>Emissions<br>Distance                       | Tachograph<br>DSRC<br>Sensors<br>GPS | www.ezv.admin.ch    |
| Spatial Cumulative Distance | N/A   |                                  |                      |   |   |                                      |                     |
| Time-in-use                 | Belgium<br>Netherlands<br>Luxembourg<br>Denmark<br>Sweden | Eurovignette                     | HGVs > 12t           | Motorways                                     | Emissions<br>Axles                                    | Paper licence                        | www.eurovignette.eu |

Table 2.1: Overview of Different Road Charging Schemes.

from 1964 [Smeed, 1964]. The report was written by a body of 11 economists and engineers commissioned by UK Ministry of Transport [Pickford and Blythe, 2006]. The study was initiated after William Vickrey<sup>5</sup>, in 1959, presented a proposal to control Washington, D.C.s traffic congestion with electronically assessed user fees. Vickrey suggested that each car would be equipped with a transponder whose personalized signal would be picked up when the car passed through an intersection. The signal would then be relayed to a computer which would calculate the charge according to the intersection and time of day, and add it to the car's bill [Arnott, 1998]. Vickrey's principles of efficient congestion pricing (summarized in [Vickrey, 1992]) was specific about charging for the marginal social cost of each trip, that charges vary smoothly over time, and that they be determined by the congestion conditions at the time of each trip. Vickrey is, with his principles of efficient congestion pricing, considered the father of electronic road use charging [Columbia University Record, 1997].

Since the development of the underlying economic principles of road charging, there has been an ongoing development in the design and complexity of charging schemes due to the rise of new technologies which enable more efficient ways of charging vehicles for their road usage. This development has gone from traditional manual toll booths, to electronic tolling schemes in the 1970-1980s allowing vehicles to pass through toll plazas without stopping and further on to today's fully automated systems based on satellite positioning technology. [Worrall, 2003] argues that while new technologies enable new policies, specific road charging policy objectives equally determine the development of new technologies and system designs.

[Demisch et al., 2009] have conducted a study on the linkages between technologies and road charging policy objectives and found that the two main policy decisions that most often determine the selection of road charging technologies are:

- The geographical scale of the road network considered

---

<sup>5</sup>Nobel Prize winning economist (1914-1996)

- The complexity of calculating the fee to be charged

The existing road charging schemes (in section 2.3.3) confirm how the geographical scale of the road charging policy implemented, can range from charging specific road segments to nationwide charging schemes including whole road networks. Furthermore, the examples show how the variety of charges range from simple fixed fees to dynamic charges that may vary according to several different parameters as for instance time of day or level of congestion. These many different road charging systems can, from a technical point of view, be classified into two overall categories [Walker and Naberezhnykh, 2009]:

- Road-side based systems, where equipment is located on the street that detects the vehicle and communicates to a central processing facility.
- Vehicle based systems, where journeys and positions are logged within the vehicle and are communicated directly to a processing facility.

Despite the wide variety of charging objectives and scheme designs, all road charging schemes are in this thesis defined as a combination of three required technical tasks:

- Collecting data
- Transmitting data
- Processing data

A number of different technologies can be used for these three technical tasks, and thereby enable the road charging of vehicles. In this section, the thesis provides an overview of the most important enabling technologies for road charging schemes and presents how these technologies work. Table 2.2 shows the enabling technologies for each of three technical tasks (developed from [Demisch et al., 2009]).

The enabling technologies are described in the following.

|                                     | Collecting | Transmitting | Processing |
|-------------------------------------|------------|--------------|------------|
| Global Navigation Satellite Systems | x          |              |            |
| Dead Reckoning                      | x          |              |            |
| Automatic Number Plate Recognition  | x          |              |            |
| Cellular Communication              | x          | x            |            |
| Dedicated Short Range Communication | x          | x            |            |
| Radio Frequency Identification      | x          | x            |            |
| Wireless Communication              | x          | x            |            |
| Geographic Information Systems      |            |              | x          |
| Supporting Information Technology   |            |              | x          |

**Table 2.2:** Enabling Technologies for Collecting, Transmitting and Processing Data in Road Charging Schemes

#### 2.3.4.1 Global Navigation Satellite Systems

Global Navigation Satellite Systems is the standard generic term for all satellite navigation systems that provide a three-dimensional positioning solution with global coverage. GNSS is a network of orbiting satellites that transmit high frequency radio signals containing time and ranging data. The transmitted data can be received by a GNSS receiver enabling users to identify antenna location anywhere around the world [Samama, 2008].

The most well known is the NAVSTAR Global Positioning System (GPS), owned and operated by the U.S. Government, which is the only fully operational GNSS system in 2010. The Russian GLONASS is also an operational GNSS but in the process of being restored to full operation [Hofmann-wellenhof et al., 2008]. These two operational systems are both military networks under national control, but are extensively used by civilians for air, land and sea navigation. At the time of writing, another two global navigation satellite systems are under development. The European Galileo is a GNSS in the initial deployment phase, scheduled to be operational in 2013 [European Space Agency, 2011] and the Chinese regional Beidou navigation system is planned to expand into the global Compass navigation system by 2015. The NAVSTAR GPS is of primary interest to the research presented in this thesis.

GNSS provides autonomous positioning by transmitting time sig-

nals along a line-of-sight from the GNSS satellites. Each satellite is a reference site which transmits radio waves picked up by the GNSS receivers in vehicles. The GNSS receivers use the radio signals from the satellites and uses time-of-arrival information to determine their location relative to the satellite reference sites. The GNSS receivers calculate the precise time as well as position (longitude, latitude, and altitude) to within a few meters. The basic operational principles are further described in Chapter 4.

#### 2.3.4.2 Dead Reckoning

Dead reckoning (DR) positioning systems rely on sensing the components of the vehicle's course and acceleration or velocity. The dead reckoning positioning method estimates the vehicle's current position based upon a previously determined position, and advances that position based upon known or estimated speeds over elapsed time, and course. DR systems therefore consist of external distance and positioning sensors, which information from can be read. Modern vehicles are often equipped with sensors that record the wheel rotation and steering direction for safety purposes such as anti-lock braking system (ABS) and electronic stability control. In high-end automotive navigation systems, dead reckoning is often implemented in order to overcome the limitations of GNSS technology alone.

There are many possible sensors that can be considered for a DR system [Samama, 2008]. For example, vehicle speed and distance travelled can be determined using accelerometers and wheel odometers and the vehicle's course can be determined using magnetic or gyroscopic compasses. Often, a combination of sensors is used for dead reckoning estimations. For example, an Inertial Navigation System (INS) is a dead reckoning system that uses a computer, motion sensors (accelerometers) and rotation sensors (gyroscopes) to continuously calculate the position, orientation, and velocity of a moving object without the need for external references [Groves, 2008]. When using several sensors in combination, a Kalman filter is used as a sensor fusion algorithm. Sensor fusion

is a method for conveniently integrating data provided by various sensors, in order to obtain the best estimate for a dynamic system's states. In navigation systems, the Kalman filtering technique is used in order to obtain an optimal navigation solution from the various measurements available.

#### 2.3.4.3 Wireless Communication

Communication between components takes place via transmission of electrical signals from a transmitter to a receiver. The transmitter converts the original message (e.g. voice, text) into electrical signals (*modulation*) that are transmitted along a selected communication channel (*transmission*) to the receiver. The communication channel is the medium that connects the transmitter to the receiver, which can be wires, coaxial cables, fiber-optic cables, or space that carries electromagnetic waves or light waves [Subramanya and Yi, 2005]. When the transmitted electrical signal is received, the receiver extracts and converts the signal back into the form of the original information (*demodulation*).

Wireless telecommunication techniques are a prerequisite for information exchange between moving objects and stationary systems. Like many other intelligent transport systems, road charging systems need to be linked with wireless communication systems to ensure mobility. Wireless communication is used as a term for transmission of information from one place to another without using cables. It is used to describe telecommunications in which electromagnetic waves carry the signal (rather than wire) over part or all of the communication path. This can be using radio-frequency, infrared, microwave, or other types of electromagnetic or acoustic waves in place of wires, cables, or fibre optics to transmit signals or data. The communication may be one-way communication as in broadcasting systems (such as radio and TV), or two-way communication (e.g. mobile phones). In general, wireless communication includes four types of communication:

- Cellular Mobile Communication (3G, GSM, GPRS)
- Short Range Communication (DSRC, Bluetooth)

- Wireless Local Area Networks (LANs)
- Mobile Ad Hoc Networks (MANET, VANET)

As it is beyond the scope of this thesis to consider in detail the nature of communication systems, refer to [Goldsmith, 2005], [Stallings, 2002] and [Bensky, 2008] for a comprehensive review of these wireless communication systems.

#### 2.3.4.4 Cellular Positioning

Cellular communication-based positioning systems use the base stations of cellular communication networks, distributed throughout the covered area for localisation and cell tracking of mobile objects. There is a number of ways in which a position can be determined in cellular communication networks. The most important techniques for cellular positioning are:

- Cell of origin (COO)
- Time difference of arrival (TDOA)
- Angle of arrival (AOA)
- Triangulation

Refer to [Ranchordas and Lenaghan, 2003], [Kos et al., 2006] and [Sage, 2001] for a complete review of the four techniques. The simplest but also the most inaccurate way is to approximate the vehicle's position by cells coordinates locating the mobile object [Stopka, 2008]. The COO method only gives an approximation of the vehicle's position. In rural areas a single cell can cover many square kilometres, while urban cells may cover a much smaller area. In the GSM network the COO positioning method can give an accuracy of less than 100 metres in urban areas and up to 30–40 kilometres in rural areas. Cellular triangulation is a technique designed to pinpoint the geographic location of a mobile phone user. Triangulation is a process by which the location of a mobile object can be determined by measuring either the radial distance or the direction of the received signal from two or three different base stations. Using algorithms, the triangulation method determines the intersection point of the mobile phone's signal from each



base station to identify its location. Using triangulation in urban areas, where there is a wide range of base stations, the user's location can be determined within about 100 meters. In rural areas, the location of the user can be determined within about 1.5 km. The accuracy is however reduced if the signals are reflected off buildings or have taken multiple paths before reaching the device.

#### 2.3.4.5 Automatic Number Plate Recognition

Automatic number plate recognition (ANPR) which is an effective means of capturing evidence which can be implemented as a parallel vehicle identification method for a road charging system. ANPR is a system designed to automatically recognize and store license plate number data on vehicles passing through a certain point. By use of optical character recognition software, the system converts video images of vehicle registration numbers taken by cameras into information for real time or retrospective matching with law enforcement and databases featuring information about ownership of the vehicle [[National Policing Improvement Agency, 2009](#)]. The ANPR system functions are deployed using two basic methods. One involves local data processing near the camera location where data are sent to a central station at a later time. The other method involves transferring the images to a central processing station where they are queued for processing and analyzed at a later time. Many ANPR systems are based on dual cameras: an infra-red camera that captures multiple images of the specific number plate and a conventional colour camera that records an image of the plate in context.

#### 2.3.4.6 Dedicated Short Range Communication & RFID

A cheaper alternative to ANPR is the dedicated short range communication (DSRC) technology also known as tag and beacon technology. Tag and beacon is conceptually the simplest form of vehicle positioning and involves vehicles having an electronic tag on the windscreen, which communicates with a roadside beacon (tag

reader), that automatically registers when a vehicle passes [Evans and Williams, 2009]. With several widely dispersed road side beacon units, the tag and beacon system allows the monitoring of the vehicle's trajectory in relation to the roadside beacon posts. The tag and beacon technology, enables the passage of vehicles without stops at toll plazas. They are based on either microwave, infra-red or radio frequencies, and can capture evidence of vehicles passing specific roads or into specified areas.

An enhanced version of the traditional tag and beacon is the DSRC technology combined with a smart card. Smart cards are devices (in credit-card size) embedded with a computer chip providing data storage and transmission capability. In road charging systems, smart cards are primarily used to store billing information [Sorensen and Taylor, 2006]. The smart card is inserted into the vehicle's windscreen-mounted DSRC tag unit from where the charges are deducted when the vehicle passes a roadside beacon. The smart cards can be multiple purpose cards, for instance combined with use for public transport.

Radio Frequency Identification (RFID) is the term used to describe the various technologies that use radio waves to automatically identify objects. A RFID system transmits the identity (in the form of a unique serial number) of an object wirelessly using radio waves. It consists of three components: tags, readers and a host computer system. The RFID system reads tags without visual contact within the readable range of up to 100 meters. A tag can include additional information in many different formats such as text, sound or video depending on the size of the tag's built-in memory [Chon et al., 2004].

Radio Frequency Identification (RFID) tags have within recent decades been used in vehicles to automate toll process for Electronic Toll Collection (ETC).

#### 2.3.4.7 Geographic Information Systems

Geographical information systems (GIS) are software systems used for collection, storage, analysis, manipulation and presentation of

geographical information. GIS are tools used for analyzing, editing and presenting spatial data onto digital maps. GIS systems are similar to traditional database management systems (DBMS) except from the fact that the records are georeferenced, meaning associated with a particular geographic location. [Reibel, 2007] highlights that the two major advantages of GIS over other DBMS are the possibility of using multiple sets of georeferenced records, called layers, in combination for joint geoprocessing and spatial analyses, and that georeferenced objects can be subjected to spatial queries, algorithms and geoprocessing across these layers.

#### 2.3.4.8 Supporting Information Technology

Supporting information technology involves a wide variety of information technologies supporting the primary technologies in road charging systems. It includes database management systems, servers, Internet applications and on-line banking protocols. The supporting technologies monitor, maintain and assist the underlying computer and network systems of a road charging system to store, process, and receive data.

## 2.4 Summary

The aim of this chapter is to create a basic for the research on GNSS-based road charging systems presented in this thesis. The chapter has provided an overview of the congestion problems in Europe and the means by which GNSS-based road charging can help to reduce congestion and its environmental impacts. The chapter also provides a classification of the many different road charging schemes, followed by an overview of existing schemes and the different technologies enabling these schemes.



## System Fundamentals

---

The preceding chapter has highlighted the concepts of road charging and the complexity of both road charging schemes and the enabling technologies. Depending on the charging objective, road charging systems can be designed in various forms and varied by both policy and technology. Within recent years, GNSS-based road charging systems have been highly profiled on the policy makers' agenda. These types of systems are technically challenging and are considered one of the most complex types of charging systems. To understand the structure and behaviour of such road charging systems, it is important to highlight the overall system architecture which is the framework that defines the basic functions and important concepts of the system.

This chapter provides a functional architecture for GNSS-based road charging systems, derived based on the concepts of system engineering, which forms a basis for the research on GNSS-based road charging systems presented in this thesis. First, a short introduction is provided followed by a presentation of the system engineering methodologies to illustrate how and why system engineering methodologies can be beneficial for GNSS-based road

charging systems. Hereafter, the system engineering concept is used as a means to determine and classify the essential functional requirements for GNSS-based road charging systems, which defines the necessary tasks that these systems must accomplish. Finally, this chapter defines the conceptual design for GNSS-based road charging systems and derives a high-level functional architecture including the main system functions and sub-functionalities.

### 3.1 Introduction

GNSS-based road charging involves charging road users for their road usage by using Global Navigation Satellite Systems to determine the vehicle's position and to detect location and road usage. As no official definition exist, a GNSS-based Road Charging System is in this thesis defined as:

A system comprised of people, procedures and interacting telematics elements forming a coherent unit that aims at charging vehicle users for their road usage by use of Global Navigation Satellite Systems.

GNSS-based road charging systems allow for cumulative distance charging (refer to section 2.3.2), where charges are calculated for each individual vehicle based on the distance driven, the time of the trip and the vehicles geographic position. Cumulative distance charging is considered a more fair and efficient way of charging as these schemes levy charge proportional to the distance travelled, and thereby reflect a usage-based approach more accurately than other charging policies. In light of these benefits, policy makers are looking at initiating nationwide GNSS-based congestion charging schemes. However, nationwide road charging on the basis of the distance travelled is technically challenging and is seen as one of the most complex schemes [Rajnoch, 2008].

Both in the Netherlands and in Denmark, nationwide GNSS-based road charging systems have been highly profiled on the policy makers' agenda but afterwards put off or cancelled. The Netherlands had, as the first country, initiated a nationwide GNSS-based road

charging scheme on the basis of the distance travelled to be introduced for the freight sector in 2012 and gradually extended to passenger cars by 2017. Due to mounting public anger with the plans for a per-kilometer based charging scheme, the Government dropped the scheduled plans. According to a survey performed by ANWB (the Dutch automobile association) [New Civil Engineer, 2010], the Dutch public thought that GNSS-based road charging was too complicated and costly to be implemented. The complexity of GNSS-based road charging systems furthermore becomes evident due to the German HGV road charging system for motorways ([www.maut.de](http://www.maut.de)), where the first phase resulted in a technical breakdown, followed by a costly reconstruction and improvement of the system.

As many other ITS applications, GNSS-based road charging systems use various technologies (computers, communications, sensors etc.) and include a continuous exchange of information within the system. The systems may be designed in various ways, depending on the charging objective. It is therefore essential to define and specify the system concepts in an overall system architecture which is the conceptual framework that defines the important concepts and the basic functions of a system and describes the relationship among them (refer to the system engineering methodology described in the following Section 3.2). In these complex systems, the system architecture becomes a central part in helping stakeholders to understand the structure and behaviour of GNSS-based road charging systems. However, little research has been done on defining a conceptual framework for GNSS-road charging systems. In general, focus has been on the technological design options rather than specifying basic system functions and architectures. Hence, this thesis deals with determining the basic functions and defining the overall system framework for GNSS-based road charging system regardless of technological design.

With the increasing demand for GNSS-based road charging systems in Europe, more attention is now being paid on defining standards and developing ITS architectures as reference for the large number of different types and combinations of GNSS-based road

charging systems that are being developed throughout Europe (refer to the European ITS Framework Architecture by [Bossom et al., 2000]). As interoperable road charging has become one of the European Commission's objectives, research projects are conducted on specifying and validating interoperability possibilities for the German, Swiss, French, Spanish, Italian and Austrian tolling schemes (see the CESARE Project by [Directorate-General Energy and Transport, 2006]). Furthermore, the Road Charging Interoperability (RCI) project is contributing to the development of an open integrated framework that enables interoperability based on existing and planned European road charging systems [RCI Project Consortium, 2008]. GNSS-based road charging is considered the next generation Electronic Toll Collection technology, as it offers greater flexibility in terms of charging by time, distance and place and do not require roadside infrastructure to record vehicle passages [Vrhovski et al., 2004].

In the following, this thesis provides a high-level functional architecture for GNSS-based road charging systems based on the concepts of system engineering.

## 3.2 System Engineering Methodology

System engineering is an interdisciplinary approach often used in planning, designing, and implementing projects which enable the realization and follow-on deployment of successful systems. It is a systematic process of bringing a system into being; ensuring effective and efficient operation and supporting the system throughout its projected life cycle [Blanchard, 2008]. System engineering methodologies emerged from the U.S. Department of Defense programs in the 1950s. These programs often involved complex requirements and high technical risk because of the use of emerging technology. Following a number of program failures, the system engineering discipline emerged to help mitigate these technical risks.

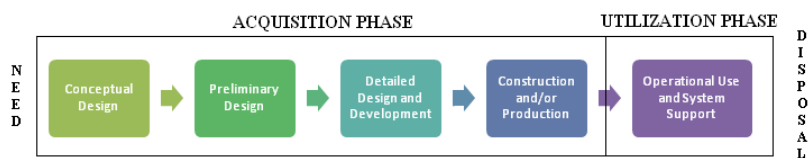
The system engineering process is a problem solving top-down ap-



proach that transforms the needs and requirements into a set of system product and process descriptions, generates information for decision makers and provides input for the next level of development. The process is applied sequentially, one level at a time, adding additional detail and definition at each level of development. The system engineering principles promote increased planning and clear system definition prior to technology identification and implementation. It helps focus on defining customer needs and required functionality early in the system development cycle [California Department of Transportation. Division of Research & Innovation, 2007].

### 3.2.1 System Life Cycle

A system engineering life cycle prescribes a number of different phases that should be followed to successfully produce and operate a system. The life cycle of a system includes the entire spectrum of activity for a given system (refer to Figure 3.1), starting with the statement of a need and ending with the disposal of the system - also known as the cradle-to-grave approach [Faulconbridge and Ryan, 2005].



**Figure 3.1:** System Life Cycle.

As shown in Figure 3.1 (inspired by [Faulconbridge and Ryan, 2005]), the system life cycle can be divided into two main phases:

- An acquisition phase, which begins with a perceived need that provides the input for the system design and ends when the system is brought into operation

- A utilization phase, which begins with system delivery; and is the final process within the system life cycle including operation and maintenance prior to disposal

The acquisition phase comprises four main activities: conceptual design, preliminary design, detailed design and development; and construction and/or production.

The first step in system engineering, is aimed at defining the conceptual design of the system by producing a clear set of system requirements based on user and stakeholder needs; and identifying the essential functions<sup>1</sup> that meets these requirements. It is important to translate the operational deployment needs into requirements early in order to address these during the system design and development activities. During this first step, the conceptual design is described in a functional manner, to avoid premature commitment to specific technology or design concepts; and a system-level functional architecture is established which meets the user needs. The functional architecture describes what is needed and which functions the system has to perform [Sage and Armstrong, 2000].

During the next step, the preliminary design is specified by converting the functional architecture into a preliminary system configuration. The preliminary system configuration describes how the system should work and the functional architecture is translated into physical design. The translation occurs through an iterative process of different activities including requirements analysis, functional analysis and allocation and design synthesis (refer to [Blanchard, 2008] for a complete view). The result of the preliminary design process is a subsystem-level design description, where the identified functions and constraints have been arranged and grouped in logical sequences; and functions have been decomposed into lower-level functional units and components. This subsystem-level physical architecture is the basic structure for generating the design specifications. In this process, the functional architecture is often revisited to verify that the physical design created can fulfil

---

<sup>1</sup>A function is specific action necessary to achieve a given objective [Blanchard, 2008]

the functional requirements and constraints. During this phase of the system life cycle, the system customer and system developers work very closely together. According to [Faulconbridge and Ryan, 2005], the customer is responsible for defining the overall system requirements, while the system developers are responsible for understanding and transforming those into detailed design specifications.

Detailed design and development is the next step in the acquisition phase. In this step, the physical architecture is used to commence development of the individual subsystems and components. It focuses on providing more detail to the architectures and generating detailed design specifications with sufficient information to commence the construction and production activities.

The final step in the acquisition phase is construction and/or production. During this activity, system components are produced in accordance with the detailed design specifications. Different test and evaluation activities are conducted to ensure that the final system configuration meets the intended purpose and fulfils the user needs; and final choices are made [Sage and Armstrong, 2000]. By the end of this activity, the system is constructed in its final form.

On delivery to the user, the system moves into the utilization phase which comprises operational use and system support. The system engineering activities continue in this phase to support any modifications that may be required regarding performance enhancement, environmental changes, maintenance needs or interoperability requirements. The support activities continue until the system is eventually phased out and retires from service [Faulconbridge and Ryan, 2005]. At the end of the utilization phase, the system's entire life cycle is completed with disposal of the system.

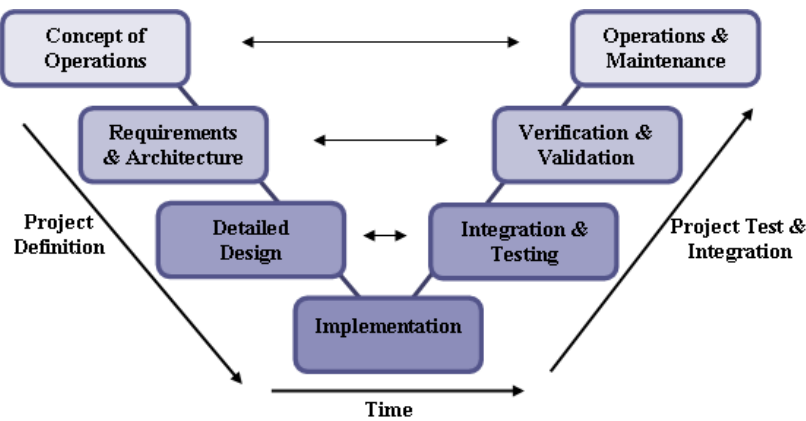
As system engineering has the largest impact during the early stages of the system development process [Faulconbridge and Ryan, 2005], the system definition (and decomposition) process during the acquisition phase is the primary focus in the system engineering process. With the different activities, system engineering focuses on the entire system life cycle and ensures that this life cycle is taken into consideration during the decision-making processes in

the acquisition phase. In this way, utilization phase requirements such as reliability and safety are considered during the acquisition phase and thereby impact on the system design early in the development.

### 3.2.2 Vee Development Model

Within system engineering, different approaches to implement these activities of the system life cycle exist. These approaches are often represented by a system development process model, which is applied with the objective of providing a logical approach to the overall process of system design and development. Several development models exist, but most of them are derivatives of the Waterfall Model, developed by Dr. Winston W. Royce for software engineering in 1970 [FDOT, 2003]. The classic Waterfall Model, demonstrates a top-down approach originally for software engineering in which the development is seen as flowing steadily downwards through the phases of system requirements, analysis, design, coding, testing and operations. Today, the most common development models used apart from the Waterfall model are the Incremental model, the Spiral model and the Vee model (see [Forsberg and Mooz, 1992] and [FDOT, 2003] for a complete review). All the various developments models help to impose discipline on developers to produce a consistent set of requirements, functional arrangements, and design solutions with the purpose of improving productivity while at the same time providing deliverables that satisfy the products end purpose.

The Vee Development Model (V-Model), developed in the 1980s, is the recommended development model for ITS projects [California Department of Transportation. Division of Research & Innovation, 2007]. The Vee Model (Figure 3.2) addresses the technical aspect of the project cycle and represents the sequence of project events. It reflects a top-down and bottom-up process designed to simplify the understanding of the complexity associated with developing systems. Within systems engineering it is used to define a uniform procedure for product or project development.



**Figure 3.2:** The Vee Development Model (inspired by [FDOT, 2003]).

The left side of the Vee Model represents the project definition development from decomposition of system requirements into preliminary design considerations and creation of system specifications. It involves an early and complete identification of project goals, a concept of operations that describes user needs and the operating environment, high level system requirement development before technology is chosen, and a detailed design description before the system is finally implemented. The system definition progresses from a general user view of the system to a detailed specification of the system design. As the system is decomposed into subsystems, the requirements are also decomposed into more specific requirements that are allocated to both subsystems and design components.

The right side of the Vee Model represents integration of the system components and their verification. It involves comprehensive testing of the implemented system to make certain it meets the stated requirements (system verification) and measuring its effectiveness in addressing the stated goals (system validation), ending with an on-going operation and maintenance process [Blanchard, 2008]. The arrows that cross the "V" represent the connections between left and right and show how plans developed on the left side, drive the right side process. The connections provide continuity

between the beginning and the end of the system development.

On both sides of the Vee Model, an iterative interaction is found between the different stages. While backward movement in the process model is not desired, it is almost inevitable between adjacent stages. For example, a desired design option may turn out impossible to implement and the design specification hence has to be reconsidered.

### 3.2.3 System Engineering Benefits

With these different step-by-step activities, systems engineering helps to transform the customers' needs to a detailed set of design requirements during the acquisition phase. System engineering thereby helps to match the customers' needs with the technical competency necessary to build the desired system. The system engineering methodology is considered beneficial for large and complex systems which often make use of state-of-the-art technology and involve large sums of money, long time scales and significant risks [Faulconbridge and Ryan, 2005]. The process ensures that the customer requirements are reflected in the design which helps to reduce costly and time-consuming changes later in the system life cycle.

Road charging systems involve people, processes and technologies and can be complex systems, depending of the purpose and nature of the charging scheme. Complex systems, which consist of several different levels of subsystems within an overall framework, are in general referred to as system-of-systems (SoS). System-of-systems are a group of part systems that produce results unachievable by the individual systems alone [Blanchard, 2008]. In a complex system-of-systems configuration, the part systems are likely to be operational in their own right, as well as be contributing in the accomplishment of the higher-level operation requirement. According to [Cole, 2006], the complexity of system-of-systems configurations strains the classical system engineering process, where system requirements are decomposed through functional architecture into detailed design. In a system-of-systems configuration,

architecture has a much stronger influence on requirements as architectural constraints imposed by existing systems and infrastructure can have a major influence on overall objectives and requirements. Cole highlights that in complex systems, where user needs and technology are continuously changing, architecture becomes a central part in understanding and defining the overall project as there are multiple system architectures, interfaces and interactions that must be thoroughly considered.

### 3.3 Conceptual Design

Based on the concepts of system engineering, the starting point for this thesis' derivation of a conceptual design for GNSS-based road charging systems is a classification of the essential functional requirements based on an understanding of the user needs.

#### 3.3.1 User needs

When specifying system requirements, it is important for the system developers to reflect upon the user needs. In a road charging system, various parties are involved with many different stakeholders. As each stakeholder may have their own set of requirements to the charging system it is important to specify the primary entities of these systems.

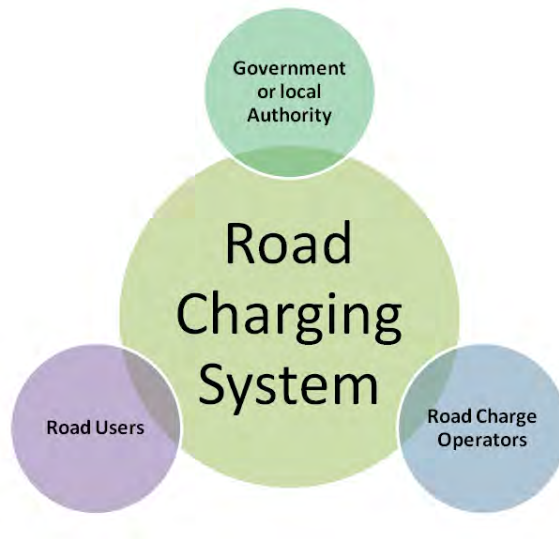
A road charging system has three primary entities (refer to Figure 3.3):

- A prime system client
- The system operators
- The road users

The prime system client is typically the government or the local authority of the charging area, who has a need for a road charging system and to whom the operational system will ultimately be delivered. Behind the system operators is one or several major subsystem providers that will operate the different functions

related to the road charging system. And finally, the road users which use the roads within the charging area and thereby also the charging system when implemented.

As each of the three primary entities has their own set of requirements to the charging system, the system requirements should be considered from all three entities' viewpoints.



**Figure 3.3:** Prime Entities in a Road Charging System.

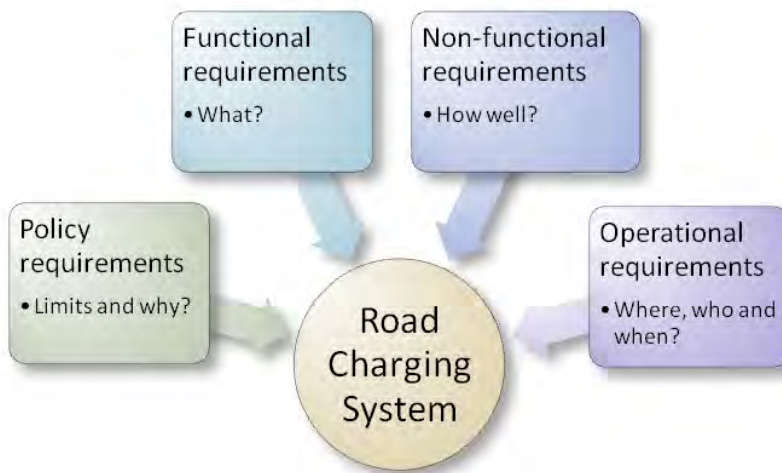
The prime system client is the overall user and customer of the system. The road charging system is "ordered" to meet a perceived need which varies from system to system. The main objective of the road charging system might be to finance new infrastructure or to manage traffic and reduce congestion and environmental impacts (refer to section 2.3.1), but for whatever reason, the system is implemented and used to achieve this desired goal. The overall requirement from the client's point of view is therefore that the system meets the system objectives. According to [Faulconbridge and Ryan, 2005], the customer is responsible for defining the overall system requirements while the system developers are responsible for understanding and transforming those into the de-



tailed design specifications.

For GNSS-based road charging systems, one common desire is to locate vehicles in relation to the road network and determine their road usage. The overall requirement can be further decomposed into more detailed requirements regarding policy, system configuration or technical performance. Hence every road charging system has its own set of requirements.

The system requirements depend on the road charging objective as they define both what the system is required to do and the constraints under which it is required to operate. The set of system requirements for GNSS-based road charging systems are in this thesis classified into four overall categories (as illustrated in Figure 3.4): policy requirements, functional requirements, non-functional requirements and operational requirements.



**Figure 3.4:** Classification of Road Charging System Requirements.

Policy requirements cover the requirements which are closely connected to the overall system objective and describe why the system is needed. Furthermore, the policy requirements include business constraints for implementation/maintenance costs, the return on investment, funding and delivery schedule, resources etc. These

requirements are typically set by the prime system client in the project definition phase (refer to Figure 3.2 on page 55) where the concepts of operations are decided. The policy requirements are supported by the operational requirements, which are requirements that decide the systems' geographical scale, operational deployment, overall system configurations (e.g. GNSS) and interoperability with other systems. The operational requirements identify who/what performs the system functions or how the functions should be operated [Pearce, 2000]. The technical requirements cover the functional and performance requirements for the road charging system. In general, functional requirements define what a system is supposed to do whereas non-functional (or performance) requirements define how a system is supposed to be.

The first written operational requirements for road charging systems in general date back to 1964, where The Smeed Report<sup>2</sup> was published. The Smeed Report [Smeed, 1964] considered the economic principles for road charging and compiled a list of the necessary operational requirements that a comprehensive road charging scheme should satisfy. The Smeed Report identified nine important operational requirements:

1. Charges should be closely related to the amount of use made of the roads;
2. It should be possible to vary prices for different areas, times of day, week or year and classes of vehicle;
3. Prices should be stable and readily ascertainable by road users before they embark upon a journey;
4. Payment in advance should be possible although credit facilities may also be permissible;
5. The incidence of the system upon individual road users should be accepted as fair;
6. The method should be simple for road users to understand;
7. Any equipment should possess a high degree of reliability;
8. It should be reasonably free from the possibility of fraud and

---

<sup>2</sup> The report describing the revolutionary study on alternative methods of charging for road use, commissioned by the UK Ministry of Transport between 1962 and 1964.

- evasion, both deliberate and unintentional;
9. It should be capable of being applied, if necessary, to the whole country and to a vehicle population expected to rise to over 30 million<sup>3</sup>.

These operational requirements are still considered valid more than 40 years after they were identified [Ochieng et al., 2008].

However, in this part of the thesis, the focus is on defining the functional requirements in order to highlight the necessary tasks that the system must accomplish, and describe the essential functions that any GNSS-based road charging system has to perform. Therefore, any commitment to specific design or operational configuration is at this point to be avoided so that the system requirements are described only in a functional manner with no technical specifications or quality constraints. It is essential to define what is required before deciding on how it specifically is to be accomplished.

User acceptance of the road charging system, is another concern for the prime system client which is negatively affected by the perceived infringement on freedom and unfairness [Jakobssona et al., 2000]. It is therefore important to consider the road users' point of view during the requirement specification.

From the road user point of view, the primary requirements for the road charging system are related to operational integrity. According to [Dunlavey, 1991] the road user needs to know that the road charging provides the benefits attributed to it and is protected against dishonest operation. Dunlavey points out three specific operational concerns:

- Accuracy of charging
- Invasion of privacy
- Charge evasion

Accuracy of charging is concerned with the road charging system having a very high degree of accuracy in its charging of the road users. A high degree of accuracy gives the road users a good sense

---

<sup>3</sup>Estimated at the time of publication of the Smeed Report.

of credibility towards the road charging system, as it is important for the road users to know that they are being correctly charged for their road usage. [Dunlavey](#) also include malfunctions and possible operator fraud in the charging accuracy concern which sets requirements to the system configuration. Another concern of the road users is the invasion of privacy. As the road charging system is charging the road users for their road usage in a specified area, it requires detecting the vehicles which is a great privacy concern for many road users. The third concern is charge evasion which is a concern from the prime system client point of view. Charge evasion involves making the system as secure as possible to avoid any fraud attempts by the users which can result in huge economic losses.

The road charge operators are mainly concerned with providing a road charging service which fulfils the functional and performance requirements specified by the prime system client.

### 3.3.2 Determination of basic functional requirements

Regardless of which system or technology solutions are adopted, road charging systems must include some basic functional requirements in order to meet the overall objective of charging road users for their road usage. The basic functional requirements represent the minimum needed but should however always be adapted to the specific case. This part of the thesis defines the general basic functional requirements needed for GNSS-based road charging systems. The functional requirements listed in this chapter have additionally been inspired by [[Federal Highway Administration, 2008](#)], [[Pickford and Blythe, 2006](#)], [[Brown, 2008](#)] and [[Directorate-General Energy and Transport, 2006](#)], although the definition of functional and operational requirements is inconsistent within the literature.

The overall concept of a GNSS-based system is to charge the road users for their individual instance of road usage. In order to do so, the system must identify both the vehicle and user and measure their individual road usage. This collected data must be dis-

tributed within the system in order to calculate and allocate a charge to the identified road user. In addition, the system should be able to process the payment from the user and manage the revenue income from several road users. Any GNSS-based road charging system should therefore as a minimum be able to:

- Identify vehicle and user
- Measure individual instance of road usage
- Distribute data and information within the system
- Calculate a charge based on road usage
- Allocate the charge to the user
- Process payment from the user
- Manage the revenue income

Each of these seven basic functional requirements can further be supported by additional functional requirements, derived in the following. In order to calculate and allocate a charge based on individual instance of road usage, the GNSS-based road charging system should additionally be able to:

- Provide continuous/discrete location determination
- Report from vehicle equipment to enable charging
- Process collected data
- Handle collection and management of data records
- Correlate user data
- Handle collection and settlement of charges and penalties

Addressing the user needs and the operational requirements from the Smeed Report, the concerns for a trustworthy system that considers the possibility of charge evasion or incorrect charging, additionally requires the system to:

- Identify violators
- Handle verification of usage detection and transactions
- Minimize revenue leakage and fraud
- Handle complaints from road users
- Produce evidence of charge evasion

To furthermore ensure security and protection of privacy, the system should in addition be able to:

- Provide means for data security
- Provide means for protecting invasion of privacy
- Secure data and voice communication
- Provide facility for system monitoring and control

And finally, to ensure system operation and user service, the GNSS-based road charging system should:

- Manage user registration
- Handle classification of vehicle characteristics
- Provide information and notification to users
- Provide facility to access in-vehicle equipment
- Manage charge exceptions and discounts
- Provide facility for system maintenance
- Provide means for system interoperability
- Manage administrative operations

The functional requirements determined in this section define essential functional requirements which this thesis states as the minimum needed for any GNSS-based road charging system.

### 3.3.3 Functional building blocks

These identified functional requirements can be transformed into a basic set of system functions that hence become the functional building blocks of GNSS-based road charging systems in general.

In the literature, [Burnham, 2008] has identified four main road charging system components which any road charging system needs from a system perspective. The article describes the characteristics of the technologies commonly considered for road charging systems and discusses different types of scheme design. [Vonk Noordegraaf et al., 2009] define a functional architecture for road charging schemes with focus on the functions that can be enabled by state-of-the-art technologies. The article highlights the technology options for the three road charging functions: Road Use Measurement, Data Communication, and Enforcement and Inspection and give a overview of the technologies available and the criteria for technology choices. In [Brown, 2008], the basic functions for

charging systems for infrastructure usage are derived. The article demonstrates how operational issues give rise to design and architectural considerations and presents a system architecture for road tolling systems including the main components and key interfaces. None of the above mentioned articles derive their functional architectures based on the system requirements, which is a prerequisite in the system engineering methodology of bringing systems into being (refer to Section 3.2).

The functional building blocks for GNSS-based road charging systems proposed in this thesis are inspired by the above mentioned literature and subsequently derived by taking into account the identified functional requirements related to both the charging process, the means for ensuring privacy and system security, the communication needed to exchange information and the requirements for system management and service that administers the entire system.

The resulting seven functional building blocks defined in this thesis are:

- User Service Management Function
- Vehicle Location Determination Function
- Communication Function
- Charge Construction Function
- Enforcement & Inspection Function
- Billing Management Function
- System Management Function

These basic system functions form the generic foundation of any GNSS-based road charging system. The relationship defined in this thesis between these functional building blocks and the defined functional requirements is given in Table 3.1.

The seven functional buildings blocks, derived in this section, form the basis for the high-level system architecture presented in the following.

| Functions                      | Functional Requirements  |
|--------------------------------|--|
| User Service Management        | Manage user registration<br>Identify vehicle and user<br>Handle classification of vehicle characteristics<br>Provide information and notification to users<br>Provide facility to access in-vehicle equipment  |
| Vehicle Location Determination | Provide continuous/discrete location determination<br>Measure individual instance of road usage<br>Report from vehicle equipment to enable charge  |
| Communication                  | Distribute data and information within the system<br>Secure data and voice communication   |
| Charge Construction            | Process collected data<br>Handle collection and management of data records<br>Calculate charge based on road usage   |
| Enforcement & Inspection       | Identify violators<br>Handle verification of usage detection and transactions<br>Minimize revenue leakage and fraud<br>Produce evidence of charge evasion  |
| Billing Management             | Correlate user data<br>Allocate charges to the road users<br>Handle collection and settlement of charges and penalties<br>Process payment from the road users<br>Handle complaints from road users   |
| System Management              | Provide means for data security<br>Manage revenue income<br>Manage charge exceptions and discounts<br>Provide means for protecting invasion of privacy<br>Provide facility for system maintenance<br>Provide facility for system monitoring and control<br>Provide means for system interoperability<br>Manage administrative operations |

**Table 3.1:** Functional Building Blocks of GNSS-based Road Charging Systems.

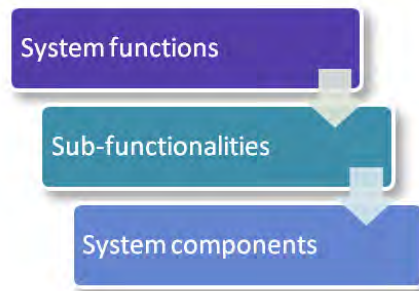


### 3.4 High-Level Functional Architecture

A high-level system architecture describes a system by defining the fundamental or logical structure of the individual components within the system's boundaries and interactions among them. More specifically, a system's architecture can be defined as follows [IEEE 1474-2000, 2000]:

"The fundamental organization of a system, embodied in its components, their relationships to each other and to the environment, and the principles guiding its design and evolution."

System architectures come in many forms and may be created from a specific perspective and be more or less detailed, focusing on specific aspects or parts of the complete system. In general, the functional architecture presents a top-level description of the system structure including its several functional blocks, sub-functionalities and components [Department of Defense Systems Management College, 2001]. Each of these functional blocks may additionally be decomposed into a series of subfunctions which can be further dissected to the component level (refer to Figure 3.5).



**Figure 3.5:** Decomposition of System Functions.

This approach enables the capture of all operational components of a system. Generally, architectures are used as a means of structuring the planning and discussion about the development of a desired system. It serves as an important communication, rea-

soning and analysis tool and becomes the point of reference to all parties involved. Especially within integrated systems, system architectures are important in order to have a clear and unambiguous understanding of the overall concepts, so that system designers can work in parallel on the development of individual basic components within the system framework [Cole, 2006]. While such an architecture does not specify the details on any implementation, it does establish the overall guidelines which must be observed when making implementation choices.

### 3.4.1 Determination of system functionalities

The seven basic system functions determined in the previous sections can be further decomposed into several sub-functionalities that are necessary for a GNSS-based road charging system. Based on the identified requirements, this section determines the main functionalities of all the functional building blocks involved in the process of road charging [Zabic, 2011b]. This determination of these system functionalities is kept generic for all GNSS-based road charging system configurations.

#### 3.4.1.1 System Management Function

The System Management function is responsible for the overall system functioning, which covers the accumulation of all functions, subsystems, methodologies and operations for the control and functioning of daily performance of the road charging system. The requirements to be satisfied by the system management function can be categorized into four functional areas:

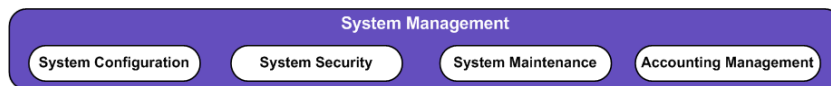
- Accounting management
- Maintenance management
- Configuration management
- Security management

The accounting function manages the system revenue and expenditures. It covers all the administrative operations and handles the

revenue management according to the charging objective and policy. The maintenance function deals with continuous maintenance of the system components. The maintenance function requires continuous information on component health and service schedules and conducts reporting on system alerts, alarms and failures to keep all system components in repair. It also maintains system warranty, licence and service organisation details [Brown, 2008].

The configuration management focuses on establishing and maintaining consistency of the road charging system's performance with its requirements and design [Gonzalez, 2002]. It includes activities (such as annual reviews and evaluations) to ensure that the system requirements are consistently being met in an effective and efficient manner. It focuses both on performance of the organization, the system functions and processes, level of service and manages any necessary changes. In addition, the configuration management directs system adjustments and ensures interoperability. Security management is related to both physical security of the road users and human resource safety functions. The security management provides means for protecting invasion of privacy. It entails the identification of information assets and the development, documentation and implementation of policies, standards, procedures and guidelines in accordance with the legislation.

These system management functionalities are in this thesis classified into the four sub-functions given in Figure 3.6.



**Figure 3.6:** System Management Functionalities.

The system management function requires continuous reporting from the remaining functional blocks to ensure that the system satisfies the overall requirements. An effective management system is crucial to ensure a smooth functioning of all system functions, leading to system success, user acceptance and economic advantages.

### 3.4.1.2 User Service Management

The User Service Management manages the road user registrations and technical installations in the vehicles. Several road user registrations may be available depending on the charging scheme. In GNSS-based systems, OBU installations are required for regular, frequent road users, which then are linked with pay-per-use accounts [Pickford and Blythe, 2006]. The user service management function manages the necessary tasks for installation, repair and service of OBU in vehicles together with the road user registrations. Road user registration requires as a minimum enough information to identify and validate the vehicle in order to link it with an account. The road user registration is therefore closely connected with the billing management function that manages the pay-per-use accounts.

In addition, the User Service Management handles support and information to the road users. Different information may be given by dynamic message signs, web-services or communication through the OBU managed by traffic managements centers or brochures and campaigns providing useful information to the road users.

These user management functionalities, are in this thesis classified into the three sub-functions given in Figure 3.7.



**Figure 3.7:** User Service Management Functionalities.

In general, the user service management function provides service to the road users before, during and after the road charging process. It assists the remaining functional blocks in providing information and assistance to the road users.

### 3.4.1.3 Vehicle Location Determination Function

The main objective of the Vehicle Location Determination function is to gather information on the vehicles' road usage by determining their position when driving by use of GNSS positioning systems (refer to section 2.3.4.1).

Determining the position of moving objects is a fundamental task for many ITS applications such as autonomous navigation and tracking of commercial vehicles. In road charging systems, the vehicle positioning is important for detecting the vehicles' driving and thereby determining their road usage. As seen from the road charging scheme examples (in section 2.3.3), GNSS-based road charging systems can be either distinct or cumulative. In distinct charging systems, vehicle positioning is applied to locate the vehicles in relation to specific roads or areas, while it is applied for continuous location determination in cumulative charging systems. In both types of charging systems, the GNSS location determination may be combined with additional measurements from cellular positioning or dead-reckoning sensors (see Section 2.3.4).

In GNSS-based road charging systems, additional measuring may furthermore be necessary for automated classification of vehicle characteristics, depending on the scheme design. Additional measuring of vehicle characteristics may be performed by sensor systems either in the surface, roadside or overhead [Persad et al., 2006]. Inductive sensors embedded in the road surface can detect the presence of a vehicle, while roadside or overhead sensors can detect vehicle height, number of axles, shape of vehicle and gaps between vehicles to provide information on the number of vehicles crossing at a specified location.

The scope of the vehicle location determination function also includes data reporting. The data reporting function collects and combines the measurement data from the positioning system and the additional sensors if applied. It selects the relevant information required and prepares data for subsequent communication to the charge construction process.

The vehicle location determination functionalities are in this thesis

classified into the three sub-functions given in Figure 3.8.



**Figure 3.8:** Vehicle Location Determination Functionalities.

#### 3.4.1.4 Charge Construction

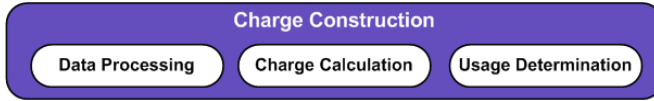
The main objective of the charge construction function is to calculate the charge based on the vehicle's road usage. The charge construction function is closely related to the vehicle location determination function and can either be integrated as an on-board function embedded in the vehicle's OBU or as an off-board function in a central server based system. The charge construction function receives the collected data from the vehicle location determination function and processes the data for charge calculations.

The scope of the charge construction function also includes data processing and summarising and sorting the locational data from GNSS or other sources available, and converting the raw data into usable information for the charging process. Furthermore, it involves validating and storing data. Based on the collected locational data, the charge construction function determines the vehicle's road usage. This is achieved by spatial analyses of data and different methods of charge calculation - either cumulative or discrete.

From the usage determination, the charge calculation determines the charge amounts to be paid corresponding to the vehicle's road usage. The charges are calculated by automated processes that for a given period (e.g. weekly or monthly) summarizes the total charge to be paid. If the charge calculation is integrated in a on-board charging function, the calculated charges can be displayed to the vehicle users. The summarized charges is forwarded to the billing management function.

The charge construction functionalities are in this thesis classified

into the three sub-functions given in Figure 3.9.



**Figure 3.9:** Charge Construction Functionalities.

#### 3.4.1.5 Enforcement & Inspection

The main objective of the Enforcement & Inspection function is to reduce the levels of unpaid charges, recover lost revenue and prevent fraud and sabotage to the system. According to [KonsULT, 2009], the enforcement strategy needs to be based on three fundamental objectives:

- Ensuring that charging policies and payment rules are followed by all road users
- Informing and raising awareness of scheme requirements to prevent non-payment
- Ensuring that the fees are paid

This is achieved by inspecting the road users to identify violators and produce evidence of fraud and unpaid charges. The evidence is used in case of complaints or to apply the charge to the correct user account and thereby ensure that the fees are paid. This can be achieved by use of ANPR technology, tag and beacon technology or by police inspection and physical barriers (refer to Section 2.3.4). Police inspection is a means of preventing fraud, as being stopped by the police and having an immediate penalty is memorable for the violator. In a GNSS-based system, police inspection of the vehicles would mean verifying that the OBU is working correctly and that the GNSS positioning function is not obstructed intentionally. However, in a large scale road charging system police inspection is limited due to the expanse of resources involved and the costs associated. This makes their use on a continuous basis

impractical, such that the probability of being stopped is likely to be low. Physical barriers can help to ensure that all vehicles entering a specific area have paid charges. With barriers, violators are identified immediately, as the barrier will not permit the violator to proceed. However, barriers also force the authorized users to slow to near-stop at the gates.

With the gathered evidence of road usage and fraud attempts, handling of users' complaints can be processed in cooperation with the billing management function. The evidential process relies on the accuracy of the evidence captured. Often a combination of the evidence extracted and associated information on time, date, vehicle location and positioning data are used to check whether a user account exists and whether the vehicle has been seen elsewhere [Pickford and Blythe, 2006]. The enforcement and inspection function thereby supports the vehicle location determination function in classification and identification of the vehicles. If the vehicle location determination function fails, road usage can be proven by use of the enforcement and inspection function and the charge can be estimated based on a combination of collected vehicle information.

The scope of the enforcement and inspection function also includes data verification, which is a very important process within GNSS-based road charging systems. Data verification takes effect as quality assurance of the charging process and features verification of the data collected, the road usage determined and the charge calculated and finally allocated. The data verification function includes database checks, process evaluations, and assessment of results.

The enforcement and inspection functionalities described above are in this thesis classified into the four sub-functions given in Figure 3.10.



**Figure 3.10:** Enforcement & Inspection Functionalities.



#### 3.4.1.6 Billing Management

The main objective of the Billing Management function is to allocate charges to road users and manage the payment processes. The core functionalities of this function are, as suggested by this thesis, covered by:

- Correlating user data
- Allocating the charges to the road users
- Applying applicable discounts
- Formatting the invoices
- Sending invoices to the road users
- Collecting information of payment transactions
- Handling road user complaints

When charges are calculated within the charge construction function, the charge data are forwarded to the billing management function, which hereafter correlates charges with user data and manages the invoice and payment processes. The billing management function manages and applies applicable discounts. In general, road charging systems can operate by prepay, post-pay, or a combination of both [Pickford and Blythe, 2006]. It is recommended that all vehicles are linked to an account, in order to provide a higher level of service to the road users. According to [Burnham, 2008], billing for road charging systems is similar to the complexity of billing within telecommunications; the challenge is getting the accurate usage data, not in applying a tariff or handling user accounts.

These core functionalities are furthermore supported by functionalities that store billing details for producing reports of billing history, and maintenance road user information for resolution of customer issues and customer relationship management. In addition, the billing management function must handle road user complaints and is therefore closely related to the enforcement and inspection function, which verifies user data and produces the necessary evidence.

These billing management functionalities are in this thesis classified into the four sub-functions given in Figure 3.11.



**Figure 3.11:** Billing Management Functionalities.

### 3.4.1.7 Communication Function

The scope of the communication function covers the distribution of information to the road charging system components in the form of voice, data and video information. This is achieved using various communication methods (see section 2.3.4.1). In GNSS-based road charging systems, the data collected needs to be communicated regularly from the vehicles to a central site in order to process charging of the vehicles. In general, the communication function provides connectivity and information transfer between road users, infrastructure and charging system providers that are both internal and external to the road charging system.

In this thesis, the communication function is represented as a link between the different functions and is not further decomposed into sub-functionalities as the communication function is very dependent on the system design.

### 3.4.2 Road charging system architecture

The system functionalities presented in the previous section are in this thesis defined as the main functionalities needed for execution, management and control in any GNSS-based road charging system configuration [Zabic, 2011b]. The defined functional blocks and their related sub-functions are presented in a generic high-level functional system architecture illustrated in Figure 3.12.

Summarized, the functional architecture defined by this thesis consists of:

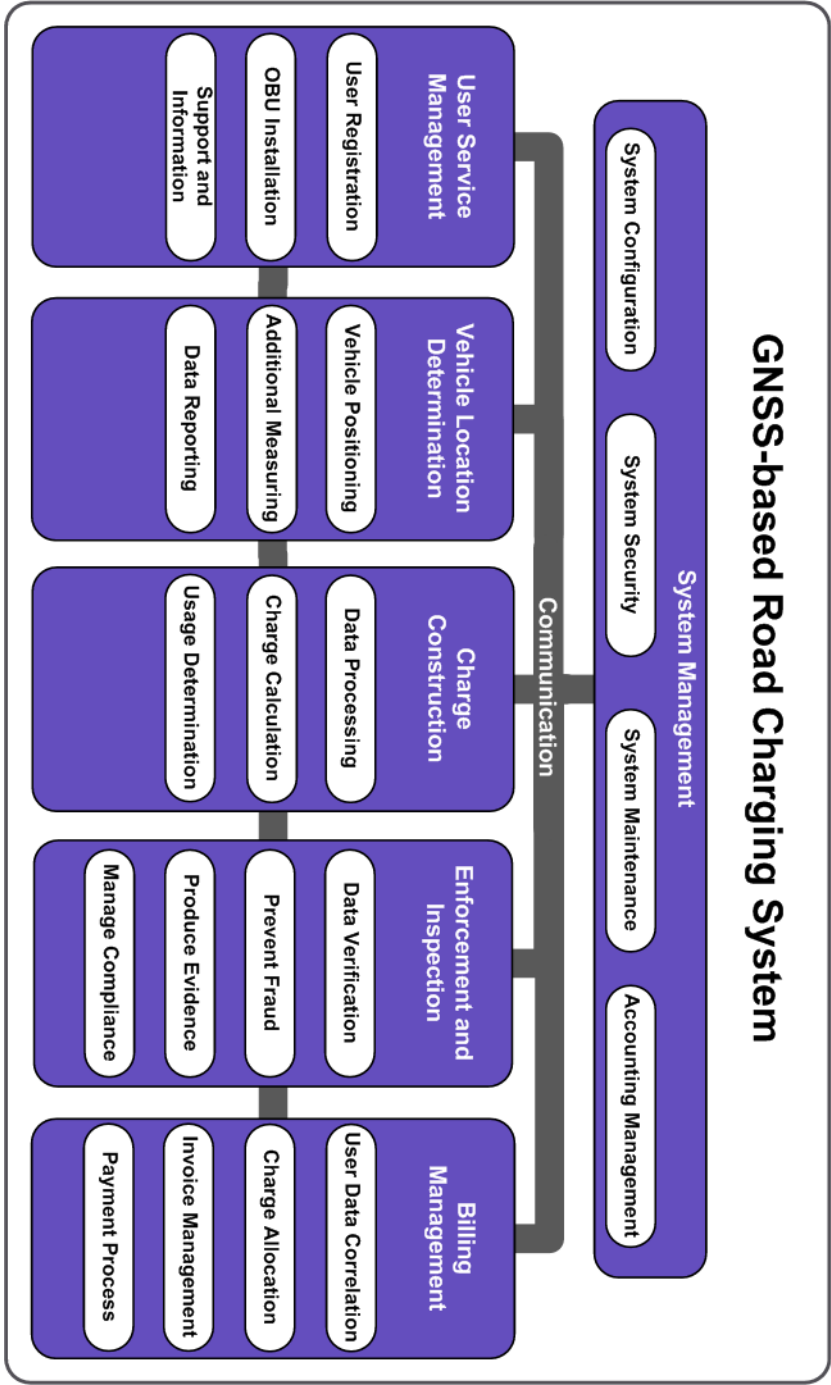


Figure 3.12: High-Level Functional System Architecture.

- A System Management function, which operates the overall system and manages the system monitoring and maintenance. It administers the revenue management according to charging objective and policy; and also directs interoperability adjustments.
- A Communication function, which represents the information flow that distribute data throughout the entire system and consists of both voice and data communication.
- A User Service Management function, which manages the road user registrations and technical installations in the vehicles. The User Service Management provides information to the road users and supports the remaining functional blocks.
- The Vehicle Location Determination function locates the vehicles' positions and in addition measures the driven distances. The function also screens and compiles the collected data in preparation for reporting.
- A Charge Construction function, which processes the vehicle location data and determines the road usage and the corresponding charges.
- An Enforcement and Inspection function which verifies data and the charging processes for documentation in case of non-compliances. The function is also aimed at inspecting road users to prevent and detect fraud and sabotage to the system.
- The Billing Management function allocates the charges to the road users and manages the payment processes.

This high-level functional system architecture presents the system functionalities independent of specific system design and is in this thesis defined as the overall functional framework for any GNSS-based road charging systems. This architecture can within future GNSS-based road charging systems become a central part for all entities involved in understanding and defining the overall project. In these complex systems where user needs and technology is continuously changing, this high-level architecture helps to maintain

the conceptual framework that defines the important concepts and basic functions of GNSS-based road charging systems.

### 3.5 Summary

There are several findings that will be taken forward from this chapter. Firstly, this chapter provided a definition of a GNSS-based road charging system and its primary entities. Secondly, system engineering methodologies were applied to determine and classify the essential functional requirements for GNSS-based road charging systems, which defines the necessary tasks that any of these systems must accomplish. These listed requirements may serve as the starting point in the planning and design of future GNSS-based road charging projects, but should however always be adapted to the specific case. Next in this chapter, the functional requirements were transformed into seven system functions for which the main sub-functionalities were defined. And finally, a high-level functional architecture was defined for GNSS-based road charging systems in general, which may serve as a common reference framework that helps to keep focus on the important concepts and basic functions of GNSS-based road charging systems.



# Performance Requirements

---

The preceding chapter defined the functional requirements and the seven functional building blocks of GNSS-based road charging systems. However, these functional requirements are furthermore supported by the non-functional requirements, which impose constraints or performance requirements on the system design or implementation. The non-functional requirements are generally measured in terms such as quantity, quality or coverage, and are usually classified according to whether they are performance requirements, maintainability requirements, safety requirements, reliability requirements, or one of many other types of requirements.

This chapter explains the overall performance requirements for GNSS-based road charging systems. First, the concepts of system dependability for GNSS-based road charging systems are introduced as a generic term for the performance requirements for road charging systems. Next, a functional flowchart of the road charging process is defined and the overall performance requirements are discussed in relation to the vehicle location determination and the charge calculation functions in the road charging process. Finally, the performance discussion is supported by an in-depth literature

review of GNSS-based road charging studies.

## 4.1 Dependability

GNSS-based road charging systems are complex systems performing many different functions using various technologies. They often involve automated processes and interaction between components and different interfaces. These complex systems rely on the performance of every single element as one failure can result in failure of the whole system and affect the dependability of the system.

Dependability is a general concept that embraces a number of non-functional requirements or key qualities which are used to assess the service delivered by a given system [De Florio, 2008]. The concept of dependability integrates attributes such as reliability, availability and safety and provides means to identify, forecast and prevent failures in systems. The field of dependability dates back to the 1940s and 1950s where the first generation of electronic computers were introduced and practical techniques were employed to improve their reliability; and then extended to other areas like military equipment, aerospace vehicles, nuclear power systems and automobiles [Deconinck and Peperstraete, 1997].

Today, the concepts of dependability are used when engineering all kinds of complex and critical component-based systems, where denial of service can have economic consequences and also endanger human life. In the field of ITS, dependability is usually linked to safety-critical applications with intelligent control systems such as adaptive driver assistance systems (ADAS), air traffic control (ATC) systems and railway traffic management systems [Gietelink et al., 2004]. In these safety-critical applications, the failure of an automated safety system (e.g. air bags) cannot be tolerated. Therefore, all aspects of dependability have to be considered in design and operation of these systems, since they are important for the responsibility of the manufacturers and the acceptability of users. Within the different technical disciplines, special procedures are developed and applied to meet the dependability requirements



specified for the system.

GNSS-based road charging systems are considered liability-critical systems, where denial of service and undetected faults and failures generate significant legal or economic negative consequences. In GNSS-based road charging systems the computed position, velocity and/or time are used as the basis for charging [Cosmen-Schortmann et al., 2008]. Any fault or failure that lead to incorrect charging may cause economic loss or provoke wrong legal decisions as the economic liability is associated to the legal aspects due to the repercussion of potential claims.

This thesis introduces the use of system dependability for GNSS-based road charging systems. Dependability is an important requirement for a GNSS-based road charging system as the system must provide fair charging and gain user trust by ensuring system reliability and liability. Dependability is therefore for this research defined as (rewritten from [Avizienis et al., 2000]):

*The dependability of a liability-critical road charging system is the ability to deliver a service that can justifiably be trusted.*

The system service to be trusted involves all the functions in a GNSS-based road charging system as correct service is only delivered when all system functions are implemented. The system functions, which are what the system is intended to do, are specified by the functional requirements (refer to section 3.3.1)

The key performance requirements for GNSS-based road charging systems involve operational integrity, charging reliability, protection of privacy and security against misuse of any kind. These key requirements are encompassed by the concepts of dependability (refer to [Avizienis et al., 2000], [Deconinck and Peperstraete, 1997] and [De Florio, 2008] for a comprehensive review), which in this research is used as a generic term for embracing the attributes which can be used to assess the service delivered by a given road charging system. The main attributes are:

- Availability: readiness for correct service
- Reliability: continuity of correct service

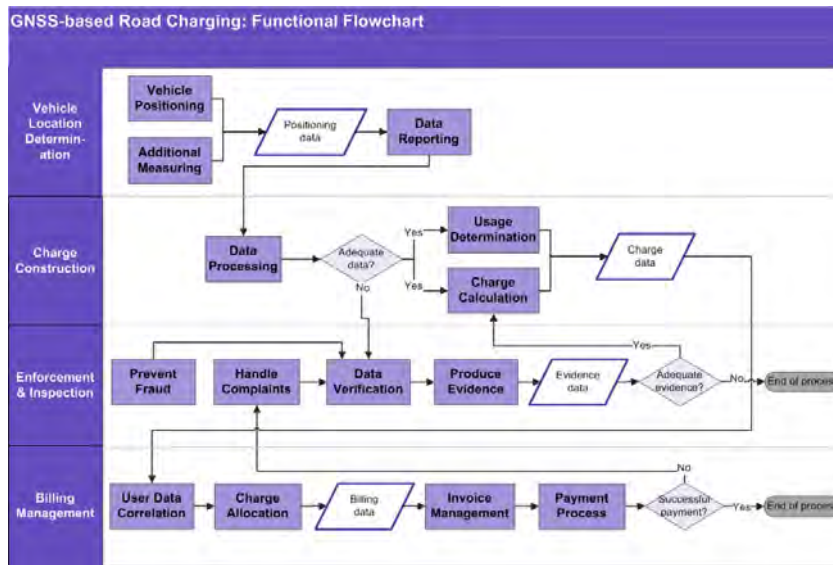
- Integrity: absence of improper system state alterations
- Maintainability: ability to undergo repairs
- Safety: absence of catastrophic consequences
- Confidentiality: absence of unauthorized disclosure of information

Depending on the system design, there may be more or less focus on the different attributes. [Avizienis et al., 2000] highlights that the extent to which a system possess these attributes should be interpreted in a relative, probabilistic way and not in an absolute, deterministic sense due to the unavoidable presence of faults. No systems are ever completely available, reliable or safe. In general, the dependability attributes can concern both systems, subsystems or single components of a system. To ensure a GNSS-based road charging system that provides fair charging and gain user trust by ensuring system reliability and liability, it is important to understand the road charging process which is the core part of a road charging system.

## 4.2 Road Charging Process

The road charging process is the key part in GNSS-based road charging systems, which consists of the four functional blocks: vehicle location determination, charge construction, enforcement & inspection and billing management (described in Chapter 3). A functional flowchart of the GNSS-based road charging process is given as defined by this thesis in Figure 4.1 below. The figure demonstrates the functional road charging flow in GNSS-based road charging systems regardless of the specific technical design chosen.

The vehicle location determination function is a prerequisite for the road charging process. The GNSS positioning function together with any additional measuring provides the positioning data that are fundamental for the road charging process. Through the data reporting, the relevant positioning information is selected and communicated to the charge construction function, where data are processed. Before determining the distance driven, an assess-



**Figure 4.1:** Functional Flowchart of the Road Charging Process.

ment of whether data are adequate for charging is necessary. If adequate, the process continues and the road usage and corresponding charge is determined. If inadequate, data verification is necessary from the enforcement & inspection function to search for evidence data. If the evidence data are inadequate as well, the road charging process ends without the possibility of charging the road users for their road usage.

When the charge is calculated, it is then communicated to the billing management function and allocated to the user by correlating user data. When the charges are allocated, billing data are given to the invoice management which finalizes the road charging process by communicating invoices to the payment process. The payment process collects the payments from the road users. If the payment succeeds, the road charging process ends with a successful charging of the road user. If the payment fails, the road user may lodge a complaint, which returns to the enforcement & inspection function that manage any non-compliances and handle users complaints by data verification and search for evidence data in order

to recalculate the charge. If evidence data again is inadequate, the specific road charging system should include specified procedures implemented to handle such cases.

To ensure a GNSS-based road charging system that provides fair charging and gain user trust, the output of the road charging process must be dependable. The Dutch Ministry of Transport has in relation to their considerations on GNSS-based road charging defined a Concept Requirement Specification [Zijderhand et al., 2006] saying:

*"99 % of the monthly invoices need to be accurate within 1 %"*

This Concept Requirement Specification requirement means that the performance of the many different components and functionalities in the road charging system, altogether must meet this overall performance requirement. The road charging process can be designed in various ways by use of different telematics technologies. In general, GNSS-based charging covers various types of approaches which employ different technologies (DR, DSRC, tachographs) and different methods of charge calculation in different geographic road network representations. However, in GNSS-based road charging systems the vehicle location determination function forms the basis for charging. The computed position, velocity and/or time are the basic input for the road charging process.

### 4.3 Navigation Function

Applications of Global Navigation Satellite Systems in intelligent transport systems are already extensively deployed as the Global Positioning System is currently supporting a wide variety of ITS applications. However, it is well known that satellite positioning in dense urban areas raises a number of difficulties due to the lack of satellite visibility in urban environments. Previous research highlights that the most important difficulties are related to signal ob-

struction caused by urban canyons, bridges and trees, in addition to multipath effects caused by reflections from the surroundings.

GNSS-based road charging systems have many advantages such as flexibility, in terms of designing and deploying charging tactics and a minimum need for external infrastructures, but the systems suffer from their technology dependency due to the nature of GNSS with random position errors and temporal obstruction of signals. These random errors and inaccuracies are of special concern for GNSS based road charging, as they can lead to unacceptable incorrect charging. With satellite-based technology there consequently still are weaknesses to overcome, as road charging systems as a liability critical application require a certain level of GNSS performance to provide a high-quality service.

In recent years, Global Navigation Satellite Systems are being introduced within Intelligent Transport Systems whenever appropriate and cost effective. Two GNSS systems are currently in operation: the United States GPS and the Russian Federations GLONASS. A third, the European Galileo system, is under development. Each of the GNSS systems uses a constellation of orbiting satellites working in conjunction with a network of ground stations.

#### 4.3.1 Global Navigation Satellite Systems

Global Navigation Satellite Systems is the standard generic term for all satellite navigation systems that provide a three-dimensional positioning solution with global coverage. GNSS is a network of orbiting satellites that transmit high frequency radio signals containing time and ranging data. The transmitted data can be received by a GNSS receiver enabling users to identify antenna location anywhere around the globe.

The most well known is the NAVSTAR Global Positioning System (GPS), owned and operated by the U.S. Government, which is the only fully operational GNSS system in 2011. The Russian GLObal NAvigation Satellite System (GLONASS) is also a operational GNSS but in the process of being restored to full operation. These two operational systems are both under national military

control, but are extensively used by civilians for air, land and sea navigation. At the time of writing, two more global navigation satellite systems are under development. The European Galileo is a GNSS in initial deployment phase, scheduled to be operational in 2014 [European Space Agency, 2011] and the Chinese regional Beidou navigation system is planned to expand into the global Compass navigation system by 2015. The NAVSTAR GPS is of primary interest to this research.

#### 4.3.2 Basic Operational Principles

The Global Positioning System is a space-based radio navigation system developed and controlled by the US Department of Defense. It consists of a constellation of minimum 24 satellites (4 satellites in 6 orbital planes) orbiting at an approximate altitude of 20.200 km every 12 hours. GPS provides 24-hour, all-weather 3D positioning and timing all over the world, with a predicted horizontal accuracy of 22 meters (95 %). In depth technical descriptions of GPS may be found in [US DoD, 2001], [Hofmann-wellenhof et al., 2008], and [Misra and Enge, 2006].

Each satellite transmits ranging signals on two carrier waves in L-band frequencies, designated as L1 and L2. The frequencies contain two mathematical codes – the Coarse Acquisition (C/A) and Precision (P) code<sup>1</sup>, which are used to separate the standard positioning service (SPS) for civile users from the precise positioning service (PPS) for military use.

Positioning in the SPS is based on the principle of time of arrival (TOA) ranging. The GPS L1 signal transmitted from each satellite contains a Navigation Message<sup>2</sup> from which the GPS receiver can estimate the satellite position and satellite clock bias relative to GPS system time. Each satellite carries precise atomic clocks to generate the timing information needed for precise positioning.

---

<sup>1</sup>L1 carries both codes, while L2 carries only the P-code.

<sup>2</sup>Including satellite information e.i. satellite clock bias data, ephemeris data, orbital information, almanac data for the entire constellation, and other general information.

Based on these signals that each visible satellite broadcast, the receiver knows the satellite's position and time of transmission of the signal. By comparing this with the signal arrival time, the GPS receiver estimates the pseudorange between satellite and receiver. A pseudorange observation is equal to the true range from the satellite to the receiver plus delays due to satellite/receiver clock biases and other error effects [Misra and Enge, 2006]:

$$R = p^t + c(\Delta t) + \epsilon \quad (4.1)$$

where  $R$  = observed pseudorange,  $p^t$  = true range to satellite,  $c$  = velocity of propagation (speed of light),  $\Delta t$  = clock biases (receiver and satellite) and  $\epsilon$  = propagation delays due to other effects such as atmospheric conditions and multipath (described in the following section 4.3.3).

The true range  $p^t$  is equal to the coordinate difference between the satellite and receiver:

$$p^t = \sqrt{(X_{sat} - X_{rec})^2 + (Y_{sat} - Y_{rec})^2 + (Z_{sat} - Z_{rec})^2} \quad (4.2)$$

If the effects of ionospheric, tropospheric, satellite orbit, and multipath error on the pseudorange are ignored, then only four unknowns remain in the equation, the 3D receiver position ( $X_{rec}, Y_{rec}, Z_{rec}$ ) and the receiver clock bias ( $\Delta t_{rec}$ ). Positioning hence requires that the GPS receiver gets signals from at least four satellites. The GPS receiver hence uses triangulation to compute its own latitude, longitude, elevation and time (refer to [Taylor and Blewitt, 2006]). Adding more pseudorange observations provides redundancy to the solution, while signals from only three satellites can be used for 2D positioning.

### 4.3.3 Accuracy and Error Sources

The accuracy of the position and velocity estimates obtained by a user depends upon the number of satellites in view at the time and their spatial distribution, and upon the nature of the errors in

the measurements [Misra et al., 1999]. There are various sources of errors that alter the accuracy of the measurements. A thorough description of these error sources is given in [Kaplan and Hegarty, 2006]. Some of the more significant components of the error budget include [US Army Corps of Engineers, 2011]:

- Receiver and antenna quality and type
- Receiver platform dynamics (static or dynamic)
- Reference frames (satellite and user)
- Geographic location of user
- Satellite configuration relative to user
- Satellite characteristics
- Satellite constellation and service availability
- Atmospheric conditions (signal propagation delays)
- Solar flux density (11-year solar cycle)
- Multipath conditions at receiver
- Receiver noise
- Receiver mask angles

However, the primary sources of errors that degrade the GPS performance are the atmospheric errors, the geometry of the satellites, multipath, timing and satellite orbit errors.

Atmospheric errors are the most significant source of errors of GPS. When the GPS signals travel through the ionosphere and the troposphere layers before reaching the receiver antenna, they are affected by charged particles (free electrons) in the ionosphere which influence the propagation of microwave signals. The error effect on the GPS range values is dependent on sunspot activity, time of day, and satellite geometry (refer to [Hofmann-wellenhof et al., 2008]). GPS operations conducted during periods of high sunspot activity or with satellites near the horizon produce range results with the highest number of errors. However, a dual frequency receiver can reduce the effect of the ionospheric refraction on the range error since the L1 and L2 signals experience different propagation delays in the ionosphere.

The spatial relationship of the satellites being tracked relative to the receiver plays a considerable role in the position solution error.



The effect of the satellite geometry on the position error can be expressed in terms of various dilution of precision (DOP) parameters. A GPS receiver constantly computes a DOP value based on the satellites being used for the computation of the position [Kaplan and Hegarty, 2006]. The better the geometry (satellites properly spread in the sky), the lower the DOP value. With all satellites confined in one part of the sky or blocked by buildings, tree etc, the geometry will be poor and the computed DOP value will be high. For applications which ignore the position elevation, the Horizontal Dilution of Precision (HDOP) is used.

Multipath occurs when the signals from the satellites are not received directly, but partially reflected from surfaces in the environment. Basically, an antenna receives the direct (line-of-sight) signal from the satellites. Multipath describes the error that occurs when the signal arrives at the receiver from more than one path due to reflecting surfaces near the GPS receiver. Multipath normally occurs near large reflective surfaces, such as trees, metal building or structure. GPS signals received as a result of multipath give inaccurate GPS positions when processed as the reflected signal usually is a weaker version of the direct signal. Since reflection surfaces are unique to each observation point and even vary over time as the satellites move, the effect of multipath signal of range measurements varies between the individual measurements. For long observation periods ( $> 24$  hours), the multipath effect will be reduced by an average, while the multipath effect for most observation periods in minutes or seconds becomes more significant. Multipath is one of the major error sources in GPS positioning (refer to [Misra and Enge, 2006]). In urban areas, where both the satellite geometry of the visible satellites is poor and the multipath effect is worst, the positioning becomes significantly degraded – also known as the urban canyon effect.

GPS satellites use high quality atomic clocks that are stable and highly accurate, as GPS relies very heavily on accurate time measurements. GPS satellites carry rubidium and cesium time standards installed in each satellite to prevent clock failures [Groves, 2008]. The clocks are checked several times a day from the con-

trol stations on Earth. However, the time offset between the time as recorded by the satellite clock and the time recorded by the receiver results in errors in the range measurements.

GPS satellites follow very precise orbits. But drifts in the satellite orbits are inevitable and very small amount can hence cause significant errors in the range measurement. Satellite ephemeris errors are errors in the prediction of a satellite position which may then be transmitted to the user in the satellite data message. The bias is the difference between the true position and velocity of a satellite and its known value [US Army Corps of Engineers, 2011]. More accurate satellite orbit data can however be obtained at later periods for post-processing, but not for real-time positioning applications.

In general, there are two main components that determine the accuracy of a GPS position solution: the Dilution of Precision (as described in the previous section) and the User Equivalent Range Error (UERE) which is the uncertainty of each pseudorange measurement. The UERE expresses the individual contribution of each bias to the overall error and hence gives the accuracy of the individual range measurements to each satellite. The positioning accuracy can be predicted by:

$$\text{Positioning Accuracy} = DOP * UERE \quad (4.3)$$

From the above, it becomes obvious that the better satellite geometry (and lower DOP), the better the positioning accuracy. Table 4.1 (adapted from [Kaplan and Hegarty, 2006]) summarizes the primary error sources and their potential error size<sup>3</sup>.

As mentioned previously, several more error contributors exist. Many of these range errors listed can be removed or minimized by use of models that can be used as a corrective supplement for the basic GPS information. Differential techniques also eliminate many of these errors (refer to [Misra and Enge, 2006] for a more detailed explanation).

---

<sup>3</sup>User range error contribution in meters

| Error Source         | Potential Error Size |
|----------------------|----------------------|
| Satellite clock bias | 2 m                  |
| Ephemeris error      | 2 m                  |
| Ionospheric delay    | 2-10 m               |
| Tropospheric delay   | 2-2.5 m              |
| Multipath            | 0.5-1 m              |
| Receiver noise       | 0.5 m                |

**Table 4.1:** Error Source and Their Potential Error Size.

With satellite-based technology there consequently still are weaknesses to overcome, as road charging systems as a liability critical application require a certain level of GNSS performance to provide a high-quality service.

#### 4.3.4 Required Navigation Performance

Determining the position of moving objects is a fundamental task for many ITS applications such as autonomous navigation and tracking of commercial vehicles. These applications hence depend on the navigation function to be available and derive correct spatial data including position, time and speed. From a user's perspective, the availability of GNSS is generally high. The use of in-vehicle navigation systems, personal tracking devices etc. works whenever needed and the accuracy of these applications seems fair. However, liability-critical applications as road charging systems in which the computed position form the basis for a charge, require a certain level of navigation performance.

The GNSS performance can be measured with the four parameters: accuracy, integrity, continuity and availability. These parameters are known as the Required Navigation Performance (RNP) and have their origin in aviation<sup>4</sup> where it is used to define the level of safety required of a navigation system, but the concept has been extended to land and marine transport modes [Ochieng, 1999]. Ac-

<sup>4</sup>Developed by The International Civil Aviation Organization (ICAO).

curacy describes the closeness of a measured position to the truth; integrity relates to the OBU's ability to provide timely warnings that performance has weakened; continuity measures the ability of the system to perform its function without interruption, during an intended period of operation; and availability describes the percentage of time the service is available for use, without outages, whatever the cause (refer to [Ashkenazi et al., 1995] for a complete explanation). The service is available when accuracy, integrity and continuity requirements are satisfied.

Tabel 4.2 shows the navigation requirements for liability-critical road applications quantified in terms of the above presented RNP parameters (derived from [Ochieng et al., 2003b] and [Feng and Ochieng, 2007]).

| Parameter    | Requirement  |
|--------------|--|
| Availability | Positioning service available at least 99 % of the time (99 % allows a maximum of 14 minutes total downtime per 24 hours)  |
| Continuity   | Maximum continuous outage of 3 minutes   |
| Accuracy     | When the service is available, the computed horizontal position must be within 30 meters of the truth 95 % of the time, and within 100 meters 99.9 % of the time |
| Integrity    | A flag should be sent to the operator at the base station within 5 minutes if the system is estimating positions in error by more than 500 meters                |

**Table 4.2:** RNP for Liability-Critical Road Applications.

Even though GNSS-based positioning are the dominating application in road transport, satellite based location determination has difficulties in meeting the required performance because of the GNSS vulnerabilities.

#### 4.3.5 Augmentation

The integration of GNSS with internal/external augmentation systems is commonly suggested as complementary characteristics to improve system performance. A number of augmentation systems

can be added to support the GNSS receiver in creating a more reliable and precise vehicle location determination. The most common discussed augmentation options are:

- Receiver algorithms (RAIM)
- Additional sensors (gyroscopes, accelerometers etc.)
- Additional GNSS systems (GLONASS, Galileo etc.)
- GPS Modernization
- Ground-based Augmentation Systems (LAAS)
- Satellite-based Augmentation Systems (WAAS)
- Pseudolites
- A-GPS

The use of GNSS augmentation systems takes many forms but all share the same basic principle of providing supplementary information whose objective is to improve GNSS performance and/or trustworthiness where the GNSS receiver is more likely to be influenced by external conditions, such as dense urban environment etc. Refer to [Drane and Rizos, 1998], [Samama, 2008], [Rapp and Balmer, 2004], [Misra and Enge, 2006] for an in-depth description of the different augmentation options.

Situations where the GNSS signals are blocked cannot be avoided. The GNSS position determination can be improved, if the GNSS receiver is integrated with other positioning systems. When the GNSS receivers are not able to receive signals from the GNSS satellites it is however possible to estimate the position of the vehicle by extrapolating the last position estimate i.e. a back up function, better known as dead-reckoning navigation that contributes to the vehicle location determination. Dead reckoning (DR) is a concept used for positioning methods that require knowledge about the vehicles starting point (the last certain position) and its subsequent distance and direction to calculate its present position. Therefore a typical DR system consists of external distance and position sensors, from where the information can be read. There are different types of sensors that can function in combination with a GNSS receiver. The list includes among others: gyroscopes, magnetometers, odometers, accelerometers, inertial sensors, tachographs, altimeters and inclinometers [Taylor and Blewitt, 2006]. With the

development of the MEMS<sup>5</sup> technology, the costs of producing and using sensors have decreased considerably, and it has therefore become possible to combine these with a GNSS receiver within a more realistic financial framework. However, with these low-cost MEMS sensors it is not possible to obtain the same accuracies as those obtained with accuracy equipment and they are not as dependable as mechanical sensors.

When the GNSS satellites are out of sight, the GNSS position is extrapolated by means of distance and angle information from these sensors. This results in a precise position determination, even when the GNSS signal is weak or absent. However, a position calculated by means of dead-reckoning systems will normally be less precise the longer the time the OBU is without GNSS reception. Hereafter, the receiver uses a Kalman filter to integrate the reliability and short-term accuracy of the sensor data with the long-term accuracy of the satellite data to a total fixed position that combines the best from both worlds. A Kalman filter compares the most recent measurements with the last calculated positions and based on a statistical weighing of these, the position accuracy is improved (refer to [Kaplan and Hegarty, 2006] for a detailed description). Another advantage of the Kalman filter is that a position can be calculated, even though there is no contact to the satellites. Kalman filters are already integrated in most hand-held GPS receivers.

As described, numerous augmentations options exist for GNSS positioning. Although they are different in cost, scale and applicability, they all aim at improving the navigation performance in terms accuracy, integrity, continuity and availability.

## 4.4 Charging Function

The main objective of the charge construction function is to calculate the charge based on the vehicle's road usage. As seen from Chapter 2, GNSS-based road charging schemes may be based on ei-

---

<sup>5</sup>Micro Electro Mechanical Systems

ther cumulative road usage or discrete events. The different types of charging schemes set different performance requirements to the charge calculation.

#### 4.4.1 Discrete Charging

In discrete road charging schemes, the charge calculation hence is based on detecting the charging events. This detection have four possible outputs [Grush et al., 2009]): a correct detection, a correct rejection, a missed detection or a false detection. The two last cause under and overcharging respectively. A missed recognition is a gain for the road user (and loss for the system) as the event that took place did not get detected by the road charging system. On the contrary, if the road user is charged for a false recognition of an event that did not take place, the false recognition will result in claims from the road user and threaten the system dependability.

To the author's knowledge, no performance requirements exist for discrete charging events, but [Toledo-Moreo et al., 2010] argue that when stated there should be two different performance requirements to avoid overcharging (for road users) and to ensure revenues by avoiding undercharging (for system authorities). The importance of deciding whether the stated requirement should be satisfied by all trips, any time in any scenario or if it should meet an overall statistical threshold, is in addition highlighted.

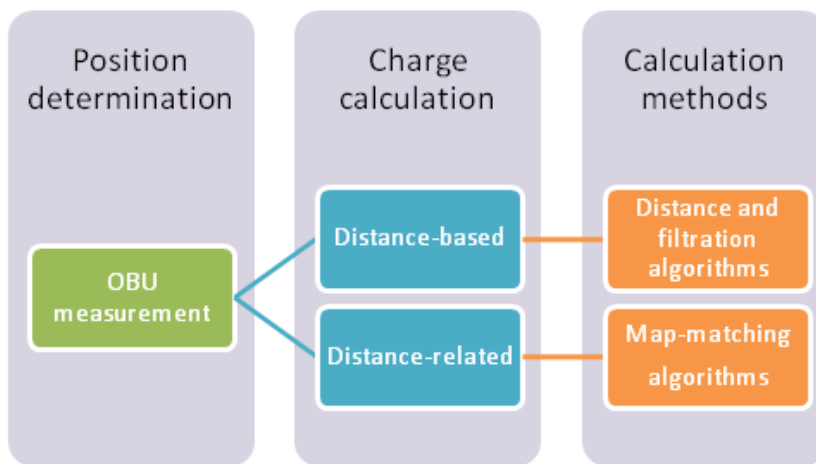
#### 4.4.2 Cumulative Charging

In cumulative road charging schemes, the charge calculation is based on one or more accumulated parameters, one of them being the distance driven. Hence several different charge calculation methodologies exist, which in this thesis are classified into two overall categories:

- Distance-based charging, based on the distance travelled as a measure of usage (i.e. kilometre).

- Distance-related charging, based on the length of the road segments used.

The distance-based charge calculation determines the charge on the basis of the accumulated distances between the individual GNSS observations, whereas the distance-related charge calculation relates the GNSS observations to road segments in a digital road network and determines the charge based on the accumulated road segments. Both schemes are scalable from the level of a single road section to an entire nation including all public roads. Different algorithms for each of the two calculation methods are available (refer to Figure 4.2).



**Figure 4.2:** Cumulative Charging Methods.

The cumulative systems primarily distinguish between whether the spatial reference should be included in the charging. The charges can be applied based on the driven distance or on time spent in the network, and this can then further be related to either zones, specific road segments or directions. The choice of system design can be both depending on what is politically desired or what is technically feasible, and presumably ends as a combination thereof. Technically, there are however significant differences in the performance of the road charging process between the various system

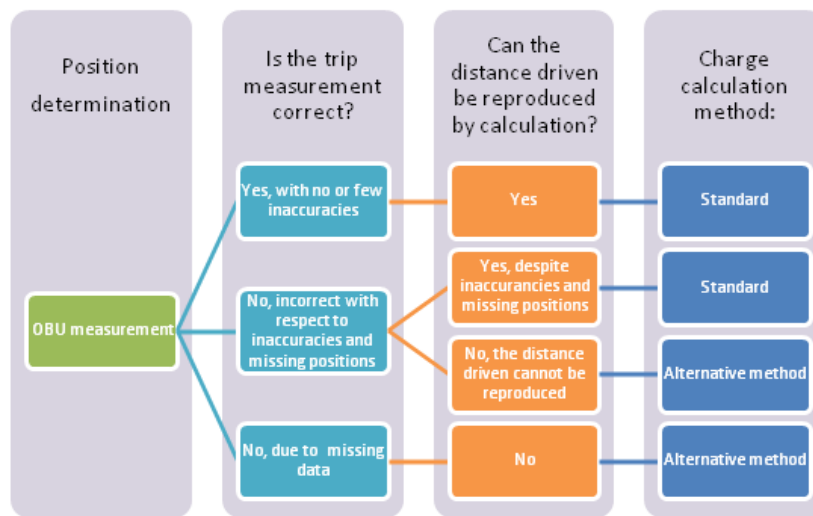


designs. The more detail to be included in the charge calculation, the greater technical demands on the system. Depending on the scheme's level of charging detail (zone, segments etc.), different methodologies may be applied.

Map-matching is a spatial analysis tool that based on an advanced algorithm, integrates the locational data with the spatial road network on a digital map [Taghipour et al., 2008]. In general, the purpose of a map matching algorithm is to identify the correct road segment on which the vehicle has driven and to determine the vehicle location on that segment. The algorithm snaps the positions or trajectory to the nearest feasible road and hence recreates the driven routes. To identify the precise road segment the map-matching algorithm mainly uses the proximity between the position fix and the road, the degree of correlation between the vehicle trajectory derived from the position fixes and the road centreline, and the topology of the road network [Quddus et al., 2007]. Orthogonal projection of the position measurement onto the selected road segment is normally used to calculate the vehicle location on the segment. Map-matching thereby enables the physical location of the vehicle to be identified on the map and is often used for navigation applications.

The two types of charge calculations categories make different demands on the position determination depending of the level of detail of the charge. In case of distance-related charge calculation, the positions are related to a digital road network, and minor GNSS fluctuations and inaccuracies are more easily evened out, and therefore the demands on the accuracy of the position determination are less strict. On the other hand, the distance-based-charge calculation is not dependent on a digital road network and is therefore not influenced by map errors and inaccuracies. Furthermore, both types of charge calculations are influenced by sources of error in the form of general algorithm errors and underestimated or overestimated filtration. It is generally common to all charging processes that the better the position determinations, the smaller the demands on the charge calculation process.

With accumulated charging, it is important for the road users' confidence in the system that the charge is in accordance with the distance driven, being at the same time important for the system that the charge levied corresponds to the vehicle's actual use of the road network. If the measurement of the distance driven is too long as compared to actual distance, the vehicle will be overcharged which highly reduces the confidence in the system. If the measurement of the distance driven on the other hand is too short, the vehicle will be undercharged as compared to the actual use of the road network thereby causing a financial loss to the system.



**Figure 4.3:** Cumulative Charging Possibilities.

The distance driven can normally be reproduced by means of calculation. Figure 4.3 illustrates the overall possibilities of the cumulative charging process [Zabic, 2011a]. In the few cases where it is not possible to reproduce the distance driven or no data have been registered, alternative methods must be used. These alternative methods include:

- Shortest path algorithms
- Distance calculations between coordinates (straight-line)

- Input from secondary enforcement system

In principle, all three alternative methods will result in undercharging of the users of the system. This can therefore lead to an increased motivation among the users of the systems to cheat the GNSS positioning in form of jamming, vandalism etc. to obtain the alternative calculation and thereby an undercharging of the distance driven. It is therefore important for GNSS-based road charging systems to ensure the accuracy and reliability of the position determination to make sure that as few as possible of the trips are calculated based on the alternative methods.

## 4.5 Literature review of GNSS-based Case Studies

In the last 10 years several GNSS based road charging studies have been carried out both inside and outside Europe. The purpose and dimension of the studies have varied, and both the technical, financial and social aspects of road charging systems have been tested in the studies. Several studies have been performed to test the accuracy and reliability of GNSS positioning in connection with both road charging systems and many other ITS applications. In the following, the methods and results from the most important studies carried out in recent years are presented. A summary of the most relevant results can be found in Tables 4.13 and 4.14 in Section 4.6.

### 4.5.1 London: Congestion Charging Trials

During the years 2003-2007 Transport for London (TfL) carried out three extensive trials (London Congestion Charging Trials - Stages 1, 2 & 3) in Central London to examine the technological possibilities and challenges of road charging systems.

In 2003, the first trial (stage 1) was initiated which a proof-of-concept study. From January to May 2004, this trial was per-

formed in order to examine how new technology could support the existing road charging system in Central London and the planned Western extension zone. The trial tested four different groups of technology with respect to accuracy and integrity. The four groups of technology are:

- Cameras and number plate recognition system (ANPR)
- Tag & Beacon systems (DSRC)
- Satellite Navigation (GPS)
- Mobile phone technology (GSM) and Value Added Services (VAS)

See the report on Stage 1 [TfL, 2005] for an explanation of the different trials and analyses. In the Stage 1 trial, the performance of the GPS was tested based on data collected from 7 different GPS devices. In the report on Stage 1 the overall purposes and results from the GPS analysis are described, whereas the description of the trial itself and the analysis method is insufficient. A description of the study method used in connection with the GPS part of the Stage 1 trial can be found in the article [Evans et al., 2005].

#### 4.5.1.1 GPS analysis in Stage 1

The purpose of the GPS analysis was to test the possibilities of using GPS in connection with road charging systems and to evaluate the performance of typical GPS devices available in the market over a range of geographical and physical conditions in Central London. In this trial, the GPS performance was assessed with respect to accuracy and integrity.

The GPS analysis tested 7 typical GPS devices in the following different versions:

- Standard GPS (not assisted GPS)
- EGNOS differential GPS
- A-GPS (assisted GPS)
- Specialized road charging equipment (OBU)

The devices included both stand-alone GPS receivers and GPS

receivers integrated in mobile phones (both GSM and 3G), which were installed in 4 cars belonging to the study. The cars belonging to the study drove through 25 chosen routes in Central London representing the different conditions under which a possible GPS based road charging system should work. In addition, the routes were designed to ensure that different kinds of driving with respect to the existing payment zone were represented, for instance when:

- driving on roads next to the payment zone (clockwise and counter clockwise)
- crossing the payment zone
- driving on a chosen route
- approaching the payment zone

Over 1,000 test runs on more than 20,000 km were made so that each of the chosen routes was traversed between 40 and 60 times [Evans et al., 2005]. All GPS measurements were compared with reference data (representing the true value) collected from three different data sources:

- Carrier Phase Differential (CPD) receivers (including GLO-NASS receiver) installed in the cars and at a reference station.
- Inertial examination of all routes with INS/Carrier Phase GPS and video cameras
- Visual examination based on video data

The analysis evaluates the performance of the GPS with respect to accuracy and integrity, defined by RNP parameters. The results from the GPS analysis in TfLs Stage 1 trial show that the average position deviation of all the devices and on all the routes is 9.7 m, and that the maximum deviation is more than 1 km [TfL, 2005]. The literature does not describe the calculation methods used and the specific results, but a comparison of the position accuracy of the seven different devices is shown in the below table [Evans et al., 2005], unfortunately without specification of the individual device type.

Table 4.3 shows the variation in the performance of the devices with respect to position accuracy.

| Device Type | Mean Error (m) | Standard Dev. | Max. Error (m) | Approx. unit costs (£) |
|-------------|----------------|---------------|----------------|------------------------|
| Device A    | 6.9            | 9.3           | 100            | Not Charged            |
| Device B    | 9.0            | 19.1          | 657            | 2000                   |
| Device C    | 9.6            | 11.8          | 637            | Not Charged            |
| Device D    | 10.4           | 13.4          | 442            | 400                    |
| Device E    | 10.7           | 21.3          | 455            | 450                    |
| Device F    | 11.4           | 15.7          | 1066           | 600                    |
| Device G    | 14.6           | 18.0          | 423            | 1200                   |

**Table 4.3:** Accuracy Comparison of the Seven Devices.

Even though the accuracy of the different GPS devices varies, none of the devices exhibited a noticeable improvement in their average accuracy. This also includes GPS devices integrated with internal augmentation systems such as dead-reckoning or differential signals [TfL, 2005].

[Evans et al., 2005] show an empirical cumulative distribution of the position deviation which states the percentage of the results that are below a given value. It is concluded that 75 % of all deviations were less or similar to 14 m and that 95 % and 99 % of all deviations are less or similar to 28 m and 57 m, respectively. This means on the other hand that 1 % of all position deviations are bigger than 57 m and the analysis therefore concludes that a buffer zone of 60 m on average is necessary at the entrances to the payment zone to ensure that the position determination is correct in 99 % of the cases TfL [2005]. At a few locations in Central London, it will be necessary to introduce buffer zones of 250 meter.

[Evans et al., 2005] describe furthermore the results of the GPS analyses examination of position integrity, based on the GPS devices own description of error ellipse of the position. As error ellipse data were not available for all seven GPS devices, the integrity analyses are based on insufficient data only stemming from individual GPS devices. The result shows that the actual position in approximately 35 % of the cases did not fall within the indicated error ellipse. In 7 % of the cases, the actual position was more than 500 m away from the error ellipse stated by the device.

The general conclusion of the GPS analysis in the TfL's Stage 1

trial is that stand-alone GPS receivers at that time did not have sufficient position accuracy to be used in connection with road charging systems in urban environments [TfL, 2006a].

#### 4.5.1.2 GPS OBU studies in Stage 2

In the beginning of 2006, the second technology trial (Stage 2) was initiated as a further development of the proof-of-concept of Stage 1 to proof-of-technical-feasibility for chosen technologies. The Stage 2 trial focused on the test of:

- Tag Beacon systems (DSRC), carried out in a mini-zone in Central London equipped with beacons and tags installed in cars belonging to the study.
- Satellite Navigation (GPS) to be used in connection with distance-based road charging systems
- Value Added Services (VAS) and back-office systems to charge calculation and charge collection.

See The State 2 report [TfL, 2006a] for a revision of the different studies and analyses.

The report [TfL, 2006b] describes methods and results from the extensive studies (GPS OBU trial) with GPS based navigation equipment and navigation systems to be used in connection with cumulative distance charging systems. The purpose of the GPS OBU trial was to obtain a better understanding of how precisely a complete GPS-based road charging system can charge a trip made in London and to evaluate the technical feasibility of a complete distance-related road charging system. Apart from tests of the measurement equipment or on-board-devices, the trial also included tests of the necessary back-office systems for charge calculation and collection of the road charge. The study tested 17 different systems (from 14 different suppliers), with a common reference and included test runs in Central London of more than 14,000 km. The 17 different OBUs were installed in between one and three cars belonging to the study, and three predefined routes through Central London were covered between 30 and 90 times for a total period of two weeks. All the systems were tested using the

following method:

- Recollection of GPS positions by means of OBU equipment installed in the cars used in the study.
- Relating of position information to individual road segments by means of map-matching to a digital road network. The process took place back-office after the trips.
- Conversion of the trip information to a charge levied in accordance with road type or time of the day. The charge calculation also took place back-office.

Thus the different distance-related road charging systems were tested at three different levels:

- Location Level: location level to evaluate whether the primary input to the system is of high quality.
- Road Segment Level: road segment level to evaluate whether the system identifies the correct trip.
- Trip Level: trip level to evaluate whether the system calculates the correct charge and the correct trip length.

The results of TfL's GPS OBU studies show that the best OBU had an average location error of 5.1 meters measured at the location level. On average the 17 OBUs had an average location error of 6.7 meters, and only one of the units had an average location error of more than 8 meters. This is an essential improvement as compared to the previous studies (Stage 1) in 2004/2005. In the report [MapFlow, 2007] there is a more detailed table showing the average position deviation of the 17 OBUs. It appears from the table that 99 % of the average position deviations fall within 37 meters.

At the road segment level, the best system (with own map-matching) identified the road segments correctly in 98.6 % of the cases, with 1 % segments identified incorrectly as being part of the trip. On the whole, for systems using their own map-matching (9 of 14) the road segments were identified correctly in 96.8 % of the cases on average. The best system (with TfL's map-matching) identified the road segments correctly in 97 % of the cases, with 4.2 % segments incorrectly identified as being part of the trip. On the whole, for



the systems using TfL's map-matching, the road segments were identified correctly in 83.6 % of the cases on average.

At the trip level, the best system had an average calculation error of 0.86 % with respect to the road charge and 0.82 % as compared to the correct trip length. On average the systems had a calculation error of 6.7 % (for charge calculation) and 5.4 % (for trip length calculation), when the systems used their own charge collection systems (9 of 14) and of 11.8 % (for charge calculation) and 10.5 % (for trip length calculation), when the systems used TfL's reference charge collection system.

In the Stage 2 trial other analyses were carried out based on which it was evaluated that Galileo will improve the satellite coverage in Central London significantly. However, even though Galileo is used there will still be areas where positioning with minimum four satellites will not be possible. The GPS OBU study concluded in the report [TfL, 2006b] that the results are sufficient for introducing, at a later time, a parallel distance differentiated road pricing alternative to the present Congestion Charge system in Central London.

In 2008 the third technology trial (Stage 3) was carried out [TfL, 2008]. The Stage 3 trial performed more detailed trials with the DSRC tag and beacon technology with primary focus on utility, aesthetics, operational issues and interoperability aspects of the different solutions tested.

#### 4.5.2 London: Imperial College Experiments

Prior to the London Congestion Charging Trials, [Ochieng and Sauer, 2002] evaluated and characterised GPS performance to positioning of vehicles in Central London. The article presents methods and results from a trial carried out in December 2000 with the purposes of evaluating the capability of the GPS to support the navigation function in advanced transport telematics applications. The experiment included, at different levels of details, GPS satellite coverage (availability), position accuracy and integrity. The experiment included a car equipped with a Leica SR9500 stand-

alone GPS receiver, and a particularly route through Central London was chosen. The route had been chosen to cover the different operational characteristics, including open country, dense urban environment, tall buildings, tunnels and bridges and areas with potential electromagnetic interference of the GPS signals. The total duration of the routes was 115 minutes, and the GPS data were logged with a frequency of 1 Hz. All GPS measurements were compared with reference data (representing the true value) represented by a digital road network in London on the scale of 1:5,000<sup>6</sup>.

The GPS accuracy was examined by means of density analyses made in ArcGIS and defined by the following three parameters:

- Fixed density: The relation between number of positions within a specific accuracy demand and the total number of positions.
- Total outage: The period during the entire duration of the trip where a specific accuracy demand was not met.
- Maximum outage: The maximum continuous period where a specific accuracy demand was not met.

The results of the density analysis are shown in the Table 4.4 [Ochieng and Sauer, 2002]:

| Accuracy level (meters) | Total outage (min) | Fix density (%) |
|-------------------------|--------------------|-----------------|
| 5                       | 96                 | 42              |
| 10                      | 82                 | 74              |
| 20                      | 72                 | 99              |

**Table 4.4:** Results of GPS Accuracy Assessment.

The table shows the results of the density analysis based on the trip's total duration of 115 minutes. The total period where an accuracy demand of 5 meters is not fulfilled is 96 minutes (equivalent to 83 % of the trip duration). The equivalent numbers for the 10 and 20 meter accuracy demands are 82 minutes (72 % of the trip duration) and 72 minutes (63 % of the trip duration). The

<sup>6</sup>Indicated plot error of 5 meters

fix-density-relation for the 5, 10 and 20 meter accuracy demands are 42 %, 74 % and 99 %, respectively. This means that 99 % of the trip's GPS positions lie within 20 meters from the middle of the road.

The result of the density analysis furthermore shows that the maximum continuous period during which an accuracy demand of 20 meters is not met, is estimated to 4.7 minutes. This estimated period is important for the choice of an alternative augmentation system, as the period states how long an alternative system will have to operate in Central London without full support from GPS.

The analysis shows that the GPS satellite coverage in London is limited. Only during approximately 38 % of the trips duration there is a minimum of four visible satellites available for positioning. If minimum five visible satellites are required (in case of integrity) the number drops to as little as 15 %. The analysis therefore concludes that the GPS satellite coverage in 2000 is too low to support GPS positioning in advanced transport telematics applications.

In a later study in 2002, Imperial College tested the integration of GPS and dead-reckoning to real time-applications in an urban environment. In the article [Ochieng et al., 2003a] the performance of different GPS receivers was tested with respect to satellite availability, accuracy and integrity. This study was also carried out in London on a special route through Central London, chosen to cover the different operational characteristics. The experiment included a car equipped with four different GPS receivers with a view to examine the differences between high precision GPS receivers for land-based measurement and GPS receivers designed to transport telematics applications. The different receivers used were:

- Geodetic GPS receiver
- Differential GPS receiver
- Stand-alone GPS receiver
- Integrated GPS/DR receiver

The integrated GPS/DR receiver was tested in GPS-stand-alone-mode and in full-GPS/DR-mode. The Dead-reckoning (DR) sen-

sors included a low-cost MEMS<sup>7</sup> gyroscope, a temperature sensor and an odometer. The total duration of the routes was 4 hours and 10 minutes, and GPS data were logged with minimum 1 Hz frequency. All GPS measurements were compared to a digital road network in London on the scale of 1:1,250<sup>8</sup>. In this study the GPS accuracy was also examined by means of density analyses made in ArcGIS and indicated by means of fix-density parameters.

Analyses of the GPS satellite coverage in London show that during 60 % and 98 % of the trip duration there is a minimum of 4 visible satellites available for positioning when using the geodetic receiver and the GPS/DR receiver, respectively. If a minimum of 5 visible satellites are required (in case of integrity) the number drops to 42.5 % and 96.5 %, respectively. The results demonstrate an improvement as compared to the study in 2000.

The results of the density analysis based on the total duration of the trip are shown in Table 4.5. The table shows the fix density relation for 5, 10, 30, 50 and 100 meters accuracy demands indicated for the different types of GPS receivers.

| Fix density [%] | Geodetic GPS | DGPS | GPS | GPS/DR (GPS) | GPS/DR (full) |
|-----------------|--------------|------|-----|--------------|---------------|
| 5 m             | 31           | 16   | 56  | -            | 43            |
| 10 m            | 48           | 24   | 81  | -            | 66            |
| 30 m            | 60           | 26   | 95  | 90           | 95            |
| 50 m            | 60           | 26   | 95  | 90           | 99            |
| 100 m           | 60           | 26   | 95  | -            | 100           |

**Table 4.5:** Results of GPS Accuracy Assessment.

The results show that the fix-density-relation is relatively low for both the DGPS and the geodetic receiver as compared to the telematics receivers. The article [Ochieng et al., 2003a] stresses that this can be due to differences in the receivers' electronic system, as the receivers are designed for different purposes and to the telematics GPS receivers being designed for more dynamic conditions. The two telematics GPS receivers have a performance of 90-95 % of the positions within 30 m from the middle of the

<sup>7</sup>Micro-Electro-Mechanical System

<sup>8</sup>Indicated plotable error of 1.25 meter

road, based on GPS alone. Only the integrated GPS/DR receiver has all the trip positions logged (before drop-outs) within 100 m from the middle of the road. The largest coherent drop-out for the GPS/DR receivers (GPS mode) was 100 seconds which is therefore the maximum period during which the DR system has to handle the positioning in Central London without support from the GPS system.

The analysis therefore concludes that the integrated GPS/DR receiver is the only one of the tested GPS receivers that can meet the required demands to positioning in connection with advanced transport telematics systems. The article stresses the importance of choosing the right GPS receiver for the right purpose, as the design of the receiver is typically optimized with respect to certain types of applications.

#### 4.5.3 London: Analyses of GPS OBU Trial Data

The Dutch Ministry for Transport has carried out a number of analyses of GPS OBU data from TfL's Stage 2 trials in London with a view to examining the effects of non-map-matching (distance-based) methods to determine the distance driven in case of road charging systems. In the report [MapFlow, 2007] the methods and results from this extensive examination carried out by MapFlow and based on the original data from TfL's Stage 2 study are presented. The purpose of this project is to understand whether the drivers' use of the road can be determined sufficiently precisely without the use of map-matching and the inherent complexity.

The MapFlow analysis is based on tests and comparisons of three different algorithms for generating distance values without the use of map-matching. The three algorithms used for the distance-based determination method are as follows:

- A simple straight-line method based on time stamped GPS raw data. The method calculates the straight line (Euclidean distance) between each consecutive GPS point projected to a Cartesian coordinate system.

- A simple filtration method based on the above algorithm with addition of a filter that takes into account the acceleration of the car. If two consecutive GPS points show that the car drives faster than  $2 \text{ m/s}^2$ , this location is eliminated in the calculation algorithm, based on the assumption that a car in Central London cannot accelerate faster than  $7 \text{ km/h}$  in one second, and that the high acceleration can therefore be due to GPS errors.
- An advanced method based on extrapolation and interpolation of the GPS points. When using this method the performed trip is not influenced by each erroneous GPS point, but instead a curve that approximates the apparent movement of the vehicle over many GPS points is formed. Similarly, the performed trip is not influenced by an acute lack of GPS points. If a GPS point fails, a curve is extrapolated based on the performed trip indicated by the GPS points immediately before and immediately after a GPS drop-out.

All three algorithms are tested in relation to the truth<sup>9</sup> according to the three parameters listed below:

- Abs% Distance Deviation is the actual driven distance deducted from the method calculated distance and expressed in absolute percentage of the length of the actual trip.
- Abs% Distance Deviation Quantiles is the empirical cumulative distribution of Abs% Distance Deviation certain for the 75 %, 95 % and 99 % quantile.
- % Distance Deviation is the actually driven distance deducted from the distance calculated by the OBU systems in the TfL's stage 2 study and expressed in positive or negative percentage of the length of the actual trip. A negative percentage therefore means that the calculated trip is shorter than the length of the actually performed trip.

The overall results of the MapFlow analyses are compared with

---

<sup>9</sup>The truth refers to the distance determined in the TfL Trials from a set of different data sources (refer to section [4.5.1](#)).

the results of TfL's map-matching analysis and shown in Table 4.6 [MapFlow, 2007]. It appears from the table that Abs% Distance Deviation (the distance deviation) varies considerably between the three calculation methods. In the straight-line method there is no filtration of the observations and this is why individual (bad) OBUs destroy the total average of the methods causing more than 113 % deviations as compared to the length of the actually performed trip. For instance one OBU had an average distance deviation of 1,143.6 %. In the report it has therefore been decided also to calculate the average of the three best OBUs. As regards the three best OBUs the distance deviation drops to below 3 %.

|  |  | Straight-line Method | Filtration Method | Sophisticated Method | Vendor Map-matching | TfL's Map-matching |
|--|--|----------------------|-------------------|----------------------|---------------------|--------------------|
| <b>Abs% Distance Deviation</b>           | Vendor Average   | 113.37 %             | 8.26 %            | 16.98 %              | 3.2 %               | 8.80 %             |
|  | Best Three   | 2.17 %               | 2.33 %            | 6.07 %               | 0.2 %               | 1.67 %             |
| <b>Abs% Distance Deviation Quantiles</b> | Can the method provide 99 % billing events with trip length deviation <1 % | No                   | No                | No                   | -                   | -                  |
|  | Percent of billing events with <1 % error (vendor average)                 | 20.24 %              | 17.6 %            | 2.45 %               | -                   | -                  |
|  | Percent of billing events with <1 % error (best three)                     | 35.1 %               | 32.5 %            | 3.1 %                | -                   | -                  |
| <b>% Distance Deviation</b>              | Percent of journeys - overestimated  | 38.42 %              | 25.22 %           | 70.4 %               | Avg.<br>3.20 %      | Avg.<br>-8.80 %    |
|  | Percent of journeys - underestimated                                       | 50.99 %              | 68.3 %            | 19.2 %               |                     |                    |

**Table 4.6:** Main Results From MapFlow Analyses of TfL's GPS Data.

In case of the filtration method, incorrect GPS observations are eliminated, and the average distance deviation of all the OBUs can therefore be improved significantly to 8.26 % of the length of the actual trip. It appears from the results that the straight-line method works well in case of good GPS positions, but not in case of bad GPS positions.

In case of the advanced method, the distance deviation is approximately 17 %. As the algorithm is designed to interpolate and extrapolate between the GPS points the method is better to form

a soft curve along the observations. Due to the design of this method<sup>10</sup>, the algorithm however loses the control for certain periods of time which results in a total high distance deviation for the advanced method. If the distance deviation for the three methods is compared with map-matching of the results from the TfL's stage 2 trial it can be seen that the average values for both Vendor Average and Best Three are lower than those of the map-matching methods. Only the results of the filtration method are somewhat comparable with TfL's map-matching algorithm.

The results of the analysis also show that a request that 99 % of all charge collections have a distance deviation of less than 1 % of the actually driven length cannot be met by any of the three calculation methods. The advanced method gives the poorest result as only 2.45 % of the charges can be calculated with a distance deviation below 1 %. That the corresponding percentage is bigger for the straight-line method than for the filtration method is probably due to the fact that the filtration algorithm also eliminates individual good GPS observations from its calculation.

% Distance Deviation states the percentage of over and undercharging, respectively, in connection with the three calculation methods with respect to the actual length. It appears from the table that both the straight-line and the filtration method are most prone to undercharge, whereas the advanced method is most prone to overcharge with respect to the distance driven. The report stresses that the reason why the straight-line method is more prone to overcharging than the filtration method, is probably that the method does not eliminate GPS (software) errors which typically result in incorrect positions.

In the analysis the results are compared with the results of the TfL's map-matching analysis. Abs% Distance Deviation is calculated for the OBU's (9 of 14) (see Table 4.7 [MapFlow, 2007]) that used its own charge calculation system (map-matching). The results show that the suppliers' best charge calculation system only had an average distance deviation of 0.1 %, whereas the largest average distance deviation is 26.8 %.

<sup>10</sup>Adaptation to several OBU's.



| Vendor Device  | Correct | Missing | Incorrect | Abs%DistDev | %DistDev |
|----------------|---------|---------|-----------|-------------|----------|
| 6              | 98.60%  | 1.50%   | 1.00%     | 0.40%       | -0.40%   |
| 5              | 98.50%  | 1.50%   | 0.90%     | 0.60%       | -0.60%   |
| 10             | 97.60%  | 2.40%   | 1.10%     | 1.30%       | -1.30%   |
| 17             | 97.50%  | 2.50%   | 1.20%     | 1.30%       | -1.30%   |
| 2              | 97.50%  | 2.50%   | 1.80%     | 0.70%       | -0.70%   |
| 15             | 97.30%  | 2.90%   | 2.80%     | 0.10%       | 0.10%    |
| 1              | 96.50%  | 3.50%   | 3.60%     | 0.10%       | 0.10%    |
| 4              | 94.80%  | 5.20%   | 10.20%    | 5.00%       | 5.00%    |
| 14             | 93.40%  | 6.60%   | 33.40%    | 26.80%      | 26.80%   |
| Vendor Average | 96.80%  | 3.20%   | 6.40%     | 3.20%       | 3.20%    |

Table 4.7: Overview of Map-matching Performance.

On the whole, for the systems using their own map-matching, the road segments were identified correctly in 96.8 % of the cases on average<sup>11</sup> with an average distance deviation of 3.20 % (overcharging) with respect to the actually driven distance. On the whole for the systems using TfL's standard map-matching, the road segments were identified correctly in 83.6 % of the cases on average with a weighted average distance deviation of -8.80 % (undercharging) with respect to the actually driven distance.

Reference is made to the report [MapFlow, 2007] for more detailed analysis results and annexes, and an extensive analysis of charge collection and payment periods.

#### 4.5.4 Holland: Anders Betalen voor Mobiliteit

In 2006, the Dutch Ministry for Transport carried out a test of the GPS performance to determine GPS accuracy and reliability in the Dutch environment with respect to the intended distance-based road charging system. The study includes analyses of reliability, position accuracy and determination of the distance driven

<sup>11</sup>Weighted average of number of trips for each OBU.

(distance deviation).

The work was carried out by ARS Consulting and documented in the report [Zijderhand et al., 2006]. The study is based on a GPS data set collected in May 2006 where 19 cars equipped with a Holux GPS receiver logged the GPS positions each second and the speed from the car's CAN-bus (twice a second) for a total of 2,363 trips. Furthermore, the equipment had a start-up time of approximately 90 seconds which means that no data are registered during the first 90 seconds of each performed trip. Approximately 17 % of the registered trips were eliminated due to errors and faulty data or extreme distance deviations. For the remaining 1,952 trips, the total GPS-distance was calculated as the sum of all distances between two consecutive (and valid) GPS points plus 1.4 times the distance between the trip's first GPS point and the previous trip's last GPS point<sup>12</sup>. An unexpected high number of trips (339 of 1,952) were less than 2 km which may be due to the non-representative participants' business driving.

The study includes analyses of reliability where a general evaluation is made with respect to the availability of GPS positioning during the start-up period and during the trips and with respect to the correctness of GPS data. The results show that in 2.1 % of the total duration of the trips there were no valid GPS positions due to cold start and driving in tunnels, garages, urban canyons, etc. Furthermore it appears that less than 0.1 % of the GPS observations have a distance of more than 50 m in 1 second, equivalent to a speed of approximately 180 km/h.

In the analysis, the GPS data are compared with a digital road network, and the result shows that during 2.4 % of the time the GPS points could not be related to the road network (within 50 meter). This is due to both errors in the road network, driving on private and foreign roads and erroneous GPS positions (e.g. due to multipath). [Zijderhand et al., 2006] estimate the latter to occur less than 1 %. Furthermore the report estimates the error contribution from time-to-first-fix (TTFF) based on estimated limit values and concluded that during 10 % (+/- 1 %) of the to-

---

<sup>12</sup>To compensate for time-to-first-fix and/or the 90 seconds start-up time.

tal time driven there are no available GPS observations. Based on the above analyses and estimates, the report states that the GPS positioning is unavailable during 13 % (+/- 2 %) of the total time, primarily due to the missing positioning before TTFF.

The report also includes analyses of position accuracy where a subset of data are map-matched to the digital road network, which in the analysis represents the true value. Each GPS point is projected on the road network and the distance between the GPS points and the road network is determined. Furthermore the road type is estimated based on the speed limit for each GPS point. The results are shown in Table 4.8 [Zijderhand et al., 2006].

| Road class   | Number of GPS positions | Average distance D(dx,dy) [m] | 95 % confidence level [m] |
|--------------|-------------------------|-------------------------------|---------------------------|
| 30 km/h      | 7,734                   | 7.4                           | 35                        |
| 50 km/h      | 18,114                  | 6.0                           | 27                        |
| 60 km/h      | 1,462                   | 8.1                           | 35                        |
| 70 km/h      | 984                     | 3.4                           | 8.5                       |
| 80 km/h      | 4,160                   | 6.2                           | 25                        |
| 100 km/h     | 220                     | 4.9                           | 11                        |
| 120 km/h     | 2,912                   | 4.0                           | 8.5                       |
| <b>TOTAL</b> | <b>35,586</b>           | <b>6.2</b>                    | <b>26</b>                 |

**Table 4.8:** Lateral GPS-position Accuracies per Road Class.

The table shows the variation in GPS position accuracy with two road categories. The average distance between the GPS observations and the true value represented by the road network is 6.2 meters. It appears from the result that the 95 % confidence interval is 1/3 higher at 60 km/h than at 120 km/h. According to [Zijderhand et al., 2006] this is partly due to the fact that the road categories with low speed are primarily found in urban areas, where the position accuracy is limited, but it is primarily due to the fact that the used map-matching was not sufficiently advanced, inaccuracies in the road network and that the vehicles are not driven exactly in the middle of the road. The average 95 % confidence interval is 26 meters (in both directions) which gives a total average 95 % confidence interval for the distance between the GPS observations and the true value of 37 meters.

In the analysis the distance deviation is examined by comparison

with odometer data from the vehicles' CAN-bus. The distances are calculated as the sum of the distances between two consecutive GPS points ranging from the trip's first log to the end of the trip. For each trip and each road category the GPS distance, the road network distance (map-matched) and the odometer distance are known. A comparison of the GPS distance and the odometer distance was carried out on a subset of data for the trips where the odometer and GPS logging started simultaneously. The results of the comparison are shown in Table 4.9 [Zijderhand et al., 2006].

| Car id   | Uncorrected       |                   |                         |                         | Corrected         |                   |                         |                         | Cost (5 cent/km) [euro] | Cost deviation [euro] | Cost deviation [%] |
|----------|-------------------|-------------------|-------------------------|-------------------------|-------------------|-------------------|-------------------------|-------------------------|-------------------------|-----------------------|--------------------|
|          | GPS distance [km] | CAN distance [km] | Distance difference [m] | Distance difference [%] | GPS distance [km] | CAN distance [km] | Distance difference [m] | Distance difference [%] |                         |                       |                    |
| 3        | 212.7             | 211.0             | 1.074                   | 0.8%                    | 211.9             | 209.7             | 2.184                   | 1.0%                    | € 10.59                 | € 0.11                | 1.0%               |
| 4        | 415.1             | 415.2             | -73                     | 0.0%                    | 413.5             | 412.1             | 1.358                   | 0.3%                    | € 20.67                 | € 0.07                | 0.3%               |
| 6        | 570.6             | 570.4             | 274                     | 0.0%                    | 568.4             | 568.7             | -340                    | -0.1%                   | € 28.42                 | -€ 0.02               | -0.1%              |
| 7        | 124.4             | 123.8             | 593                     | 0.5%                    | 123.9             | 123.4             | 551                     | 0.4%                    | € 6.20                  | € 0.03                | 0.4%               |
| 8        | 246.0             | 243.8             | 2.196                   | 0.9%                    | 245.0             | 242.8             | 2.173                   | 0.9%                    | € 12.25                 | € 0.11                | 0.9%               |
| 9        | 330.0             | 329.8             | 227                     | 0.1%                    | 328.7             | 325.9             | 2.755                   | 0.8%                    | € 16.43                 | € 0.14                | 0.8%               |
| 12       | 235.8             | 236.2             | -561                    | -0.2%                   | 234.7             | 235.4             | -751                    | -0.3%                   | € 11.73                 | -€ 0.04               | -0.3%              |
| 13       | 512.1             | 513.3             | -1.179                  | -0.2%                   | 510.1             | 509.6             | 436                     | 0.1%                    | € 25.50                 | € 0.02                | 0.1%               |
| 14       | 398.3             | 395.9             | 2.454                   | 0.6%                    | 396.7             | 396.1             | 675                     | 0.2%                    | € 19.84                 | € 0.03                | 0.2%               |
| 15       | 322.9             | 322.6             | 265                     | 0.1%                    | 321.6             | 321.5             | 124                     | 0.0%                    | € 16.08                 | € 0.01                | 0.0%               |
| 19       | 180.8             | 180.0             | 789                     | 0.4%                    | 180.1             | 178.4             | 1.683                   | 0.9%                    | € 9.00                  | € 0.08                | 0.9%               |
| 21       | 424.4             | 425.0             | -644                    | -0.2%                   | 422.7             | 422.8             | -127                    | 0.0%                    | € 21.13                 | -€ 0.01               | 0.0%               |
| 22       | 128.7             | 128.1             | 549                     | 0.4%                    | 128.1             | 127.7             | 485                     | 0.4%                    | € 6.41                  | € 0.02                | 0.4%               |
| 23       | 1,198.8           | 1,201.5           | -2,712                  | -0.2%                   | 1,194.0           | 1,196.3           | -2,304                  | -0.2%                   | € 59.70                 | -€ 0.12               | -0.2%              |
| 24       | 3,197.1           | 3,191.7           | 5,379                   | 0.2%                    | 3,184.4           | 3,190.3           | -5,905                  | -0.2%                   | € 159.22                | -€ 0.30               | -0.2%              |
| 26       | 988.3             | 986.6             | 1,664                   | 0.2%                    | 984.4             | 983.0             | 1,353                   | 0.1%                    | € 49.22                 | € 0.07                | 0.1%               |
| 27       | 348.9             | 350.1             | -1,137                  | -0.3%                   | 347.5             | 348.1             | -598                    | -0.2%                   | € 17.38                 | -€ 0.03               | -0.2%              |
| 29       | 396.2             | 395.0             | 1,280                   | 0.3%                    | 394.7             | 392.0             | 2,684                   | 0.7%                    | € 19.73                 | € 0.13                | 0.7%               |
| 31       | 1,917.8           | 1,926.8           | -9,004                  | -0.5%                   | 1,910.1           | 1,916.3           | -6,147                  | -0.3%                   | € 95.51                 | -€ 0.31               | -0.3%              |
| All cars | 12,148.8          | 12,146.8          | 2,035                   | 0.0%                    | 12,100.4          | 12,100.1          | 291                     | 0.0%                    | € 605.02                | € 0.01                | 0.0%               |

Table 4.9: Comparison of GPS and Odometer Distances.

Across trip lengths and all road types, the average deviation turned out to be less than 1 % and for trips over 400 km it was reduced to 0.3 %. For the regular short trips in and around urban areas the deviation was considerably bigger than 1 %. It also appears from the table that there is a minimal variation between the different vehicles which indicates that both the GPS and odometer measurements are consistent.

In the analysis the average GPS deviations are calculated per vehicle and per road category. GPS deviations are calculated in meter per kilometer. The results for chosen road categories (as a mean of the vehicles) are shown in Table 4.10 [Zijderhand et al., 2006].

| Road class       | GPS-deviations per km |              |
|------------------|-----------------------|--------------|
|                  | In meters             | In %         |
| 50 km/h          | 16 +/- 92             | 1.6 +/- 9.2  |
| 80 km/h          | 7 +/- 6               | 0.7 +/- 0.6  |
| 100 km/h         | -2 +/- 16             | -0.2 +/- 1.6 |
| 120 km/h         | 0.6 +/- 10            | 0.06 +/- 1.0 |
| Unknown          | 2 +/- 23              | 0.2 +/- 2.3  |
| All road classes | 4 +/- 22              | 0.4 +/- 2.2  |

**Table 4.10:** Calculated GPS Deviations in Meter per Kilometer per Road Category.

The table shows that the GPS distance is generally bigger than the odometer distance. According to [Zijderhand et al., 2006] this is probably due to the zigzag deviation of the GPS position which gives a longer distance with respect to the right line. At the same time it appears that the GPS deviations are biggest in urban areas (low speed) as the accuracy for roads with a permitted speed of 50 km/h is 16 +/- 92 meter per km. The total GPS deviation for all road categories is 4 +/- 22 meter per km.

The most important conclusions from the extensive studies including different road types and a wide range of environments are:

- Time-to-first-fix is the largest problem, but it can be solved;
- For bigger distances GPS determines the distances with sufficient accuracy;
- For shorter distances the accuracy is not sufficient;
- High position accuracy is only necessary along the borders to payment zones as the combination of GPS, a common digital map and a simple map-matching algorithm can result in missing accordance (erroneous registration) at these zone borders.

#### 4.5.5 Singapore: Mitsubishi Heavy Industries

In 2007 Mitsubishi Heavy Industries developed and tested an OBU prototype with combined GPS and DR technology in Singapore [Ohno et al., 2007]. The OBU was developed with a view to be-

ing able to calculate the distance driven within predefined virtual payment zones and thereafter to calculate the equivalent charge. Mitsubishi Heavy Industries tested this prototype OBU in dynamic studies with different routes through three virtual payment zones in different environments<sup>13</sup> in central Singapore.

The study included a car equipped with OBU and GPRS communication and a central system (back-office) to receive the calculated charge from the OBU. The study was designed in such a way that when the OBU registered that the car had crossed the border to a virtual payment zone, the distance measurement took place until the car had left the zone in question again. Afterwards, the corresponding charge was calculated and sent via GPRS to the central system. The OBU consisted of:

- A GPS receiver
- A CPU (processor)
- A pulsometer attached to the odometer of the car
- A direction sensor
- A Kalman filter for filtration of GPS and DR input

The OBU stores the GPS position data, the accumulated distance calculation and the calculated charge in its internal memory. The central system only receives the calculated distance and charge. The study tested the OBUs ability to register the entrance to the virtual payment zones and the accuracy of the distance calculation within the zones.

The results of the study show the measured erroneous distances between a defined zone border and each zone registration position for the trips performed within the three different payment zones. It appears from the results that there are more major erroneous distances (10-20 meter) in case of payment zones in dense urban environments (urban canyons) than in case of payment zones in the commercial district and in the suburban districts. Generally all the erroneous distances measured in the three payment zones did not exceed 20 meter. The article therefore concludes that a buffer zone of 20 meters is necessary in the direction of travel at

---

<sup>13</sup>Urban canyon area, commercial district, and suburban district.

each zone border.

The study also tested the accuracy of the calculated distance within the payment zones. The result is shown in Table 4.11 [Ohno et al., 2007].

|                     | Reference distance (m) | Max. distance error (m) | Max. error (%) |
|---------------------|------------------------|-------------------------|----------------|
| Urban canyon area   | 587                    | 11                      | 1.9            |
| Commercial district | 725                    | 9                       | 1.2            |
| Suburban district   | 1889                   | 8                       | 0.4            |

**Table 4.11:** Accuracy of the Calculated Distance.

The table shows that the accuracy of the calculated distance is better outside the urban area. The maximum erroneous distance found in dense urban environments is 11 meter. Generally, the maximum errors are below 2 % for the calculated distances within all three payment zones. The article concludes that the tested OBU used alone is capable of obtaining the practical usage level for zone border determination and distance calculation without position corrections based on map information.

#### 4.5.6 Denmark: AKTA Experiment

In Denmark, Copenhagen participated in the PROGRESS project with a road pricing trial (AKTA) based on satellite positioning. The experiment was co-funded by the EU-project PROGRESS where other experiments with road pricing were carried out in other European cities.

The aim of the AKTA experiment was to test whether road use taxes would change travel behaviour (refer to [Nielsen and Sørensen, 2008] for a description of the behavioral results). The AKTA experiment was conducted in 2001-2003 and included 500 cars equipped with GPS receivers. Since there was no standard equipment, special OBUs were developed to record the coordinates and tariff levels based on GPS technology. GPS data was logged, when cars were in motion, and a very large and complete set of data was collected. AKTA tested three different pricing schemes – two zone-based schemes with cumulative distance charging and a discrete



scheme with payment for zone crossings and developed a map-matching algorithm for the experiment. The AKTA experiment gave detailed knowledge about the technical aspects of GPS-based road pricing [Nielsen and Würtz, 2003].

Generally, the GPS technology caused much more problems than anticipated [Nielsen, 2002]. About 90 % of the trips had gaps in the positioning, 3 % hereof to an extent where the trip could not be recreated afterwards. The most common cause for short outages (less than 5 min) was signal fallouts during the trip, but also receiver start-up time, driving in urban canyons, tunnels, garages and under trees resulted in short positioning outages [Nielsen, 2003]. Large outages (more than 5 min) were primarily caused by installation problems and defect units. In addition the results showed that the distance between the first position and the last position from previous trip was less than 30 meters for the majority of trips.

The results furthermore showed that reduced accuracy was less frequent in the data set. With sufficient visible satellites to estimate a position, the position accuracy was pretty precise. In some cases the positioning accuracy was affected systematically when the vehicles drove fast in curves – e.g. on motorway ramps. In addition it was concluded that poor position accuracy had some impact on the post-processing of the observations. The AKTA results furthermore demonstrated that the segmentations in trips were some times defined wrongly due to signal fallouts, significant bottlenecks and faults while other trips (chains) on the contrary were wrongly joined into one trip. It was also found that several vehicles had significantly more fallouts than others. Vehicles with metal filters in the front window or with very vertical windows, had problems with signal reception. In general, several different technical problems occurred during the experiment, resulting in [Nielsen, 2002]:

- 46 % of the participants experienced technical problems
- 5 % experienced that the battery was discharged
- 14 % had a unit that stopped working
- 5 % had a non-working unit at a given time during the ex-



periment

The AKTA experiment concluded that far more work is needed to address the technology issues, if a GPS-based road charging system is to be implemented at full-scale.

In [Zabic, 2004] the positioning performance in Copenhagen was assessed based on the AKTA positioning data. The positioning data were analyzed in order to determine whether the GPS quality and reliability is adequate for implementation of a road pricing system. Both the satellite visibility and the horizontal dilution of precision were analyzed in relation to the density of the built-up areas by use of different digital maps in a GIS. The results from the analysis showed that the satellite availability was inversely proportional with the building density in Copenhagen. The narrow street canyons in downtown Copenhagen prevented a sufficient amount of satellite signals to reach street level, which caused too many gaps in the position logs [Zabic, 2005]. The assessment concluded that the satellite availability in Copenhagen was not sufficient in 2003 to form the basis for a reliable operational road pricing system based on stand-alone GPS.

In 2005, a Galileo Simulator was developed to simulate the anticipated satellite visibility and positioning quality in Copenhagen with the upcoming Galileo system (refer to [Jensen et al., 2005]). With a 3D city model of Copenhagen, a Galileo simulator, and a ray-tracing algorithm, an analysis of the GNSS availability in the streets of Copenhagen was carried out. The analysis focused on the number of visible satellites and the HDOP. The results (refer to Table 4.12) showed that the satellite availability, given both by the number of visible satellites and by the HDOP, was slightly better with Galileo than with GPS, and the situation was considerably improved if GPS and Galileo were used in combination. The results also showed, however, that there will still be streets in downtown Copenhagen where the receiver-satellite geometry represented by the HDOP is not sufficient for reliable positioning during the full 24 hours of a day, even when combined GPS-Galileo receivers are introduced.

|                    | Mean | Std. dev. |
|--------------------|------|-----------|
| <b>GPS</b>         |      |           |
| Number of SVs      | 6.5  | 1.8       |
| <b>Galileo</b>     |      |           |
| Number of SVs      | 6.4  | 1.5       |
| <b>Galileo/GPS</b> |      |           |
| Number of SVs      | 12.3 | 3.4       |

|                    | Mean | Std. dev. |
|--------------------|------|-----------|
| <b>GPS</b>         |      |           |
| HDOP               | 2.6  | 5.0       |
| PDOP               | 4.3  | 7.0       |
| <b>Galileo</b>     |      |           |
| HDOP               | 2.4  | 4.7       |
| PDOP               | 3.9  | 6.2       |
| <b>Galileo/GPS</b> |      |           |
| HDOP               | 1.5  | 2.6       |
| PDOP               | 2.3  | 3.3       |

**Table 4.12:** Mean and Standard Deviation of Number of Visible Satellites and HDOP for GPS Only, Galileo Only, and Combined Galileo/GPS (24 hour simulation).

#### 4.5.7 Discussions on Literature

It appears from the literature study that the average obtainable position accuracy in dense urban environments in Europe (London and Holland) is approximately 6-12 m, a result which can therefore also be expected in Denmark. In London the results showed that 99 % of all observations fell within an accuracy demand of 20 m (using only GPS) and that all 100 % fell within 100 m (using GPS+ DR). However, if you look at the spread of the results, it can be seen that when using GNSS there may appear significantly worse accuracies, often characterized by large sudden deviations (sudden jumps) of hundreds of meters. It is therefore normally recommended to introduce buffer zones around zone borders to avoid that the charge calculation is based on equivocal GNSS observations. However, these large deviations only make up a small percentage (0.1 % in Holland) and can be eliminated by means of algorithms.

Generally, the number of visible satellites available and the HDOP value (the importance of the location of the satellites with respect to the receiver) is used to evaluate the GNSS positioning quality in different urban environments, even though these parameters do not represent the full picture of the positioning quality. In this connection, the results for Denmark show an essential improvement of the positioning quality during the last 5 years as the distribution of number of visible satellites is considerably higher and as the number of roads with deteriorated positioning quality has dropped significantly. The number of visible satellites can also be used to evaluate the GNSS availability with respect to the trip duration. The results from London show an improvement as compared to the two studies performed in 2000 and 2002, respectively. In 2000 there was a minimum of 4 visible satellites during 38 % of the trip's duration in Central London, whereas in 2002 there was a minimum of 4 visible satellites during 98 % of the trip's duration. Similarly, the maximum coherent drop-outs in connection with the GPS-stand-alone positioning improved from 4.7 minutes in 2000 to 100 seconds in 2002. It was evaluated that the increasing availability of visible satellites is primarily due to the development of GNSS receivers.

It also appears from the literature study that there are not many comparable tests of the use and the possibilities of internal augmentation systems in connection with road charging systems. From the few studies that have been carried out it does not appear which results belong to which OBU and it is often difficult to obtain the details from the manufacturers. Generally, the results look promising for the use of dead-reckoning systems (London and Singapore). In the analysis from London it is concluded that the integrated GPS/DR receiver is the only tested GPS receiver that meets the requested positioning demands in case of advanced transport telematics systems. Today, Kalman filtration is an integrated part of the available OBUs in the market just as HSGPS receivers have substituted the standard GPS receivers of most of the manufacturers.

Calculation of the distance driven can generally be performed by

map-matching to a digital road network (distance-related) or by means of other calculation algorithms (distance-based). MapFlow tests three different distance based calculation algorithms with different levels of details and compares them with map-matching results. The results hereof show a large variation in the results obtained across calculation methods. The results from London show that when using the best map-matching algorithm a 0.1 % deviation from the driven distance can be obtained, and that the poorest results give a deviation of over 25 %. This underlines the importance of choosing the right combination of OBU and calculation algorithm to obtain the best results for the charging process. On average there is a deviation of 3.2 % from the vendors' own map-matching algorithm that, on average, map-matches correctly in 96.8 % of the cases (with an average location error of 6.7 meter). The results also show the importance of using filtration of the GPS position in connection with the distance calculation. None of the results can obtain a 99 % charge collection with less than 1 % error.

The results of the Dutch analyses show that distance calculation with GPS on average deviates less than 1 % from distance calculation performed with an odometer. The analysis stresses that the distance calculation is generally a little longer with GPS than with an odometer, and that the deviation is biggest for short distances. It is estimated that integration of GPS with an odometer is not useful for the accuracy of the distance calculation itself, but that it can be useful as a secondary measurement method during the percentage of the time that the GPS positioning fails (e.g. under time-to-first-fix).

The literature generally focuses on what is possible rather than on what is not possible. Often it is not clearly described which errors and shortages that have been used to define the data as being invalid or to exclude them from the data set. In the Dutch analysis 17 % of the GPS data are eliminated and the GPS points are declared invalid in 2.1 % of the total duration of the trips. It was concluded that more focus should be placed on the errors occurred, the error rates and their importance for the charging

process in order to eliminate an even bigger part of the sources of error and obtain a higher system reliability. The results underline the importance of data validation before the charge calculation, as invalid data and coarse registration errors can give rise to serious errors when charging the users of the system.

## 4.6 Summary

This chapter has explained the performance requirements supporting the conceptual design of GNSS-based road charging systems. The concept of system dependability adapted from electrical engineering has been introduced for liability-critical road charging systems and in addition the overall performance requirements have been presented for the vehicle location determination and charge calculation in the road charging process. A functional flow-chart of the road charging process in GNSS-based road charging systems has furthermore been defined in this chapter. Finally, an in-depth review of GNSS-based road charging studies has been provided, summarizing the most relevant existing performance results for the road charging process.

| Study/years                       | Devices/duration                            | Technology                     | Test purposes                            | Description   | Results     | Source                     |
|-----------------------------------|---|--------------------------------|--|---|-------------|----------------------------|
| London Stage 1 (2004)             | 7 GPS devices, 4 cars, 25 routes, 20,000 km | GPS, A-GPS, Differential EGNOS | GPS accuracy                             | Average location error  | 9.7 m       | [TfL, 2005], [Evans, 2005] |
|                                   |   |                                |  | Maximum position deviation  | 1066 m      |                            |
|                                   |   |                                |  | Average zone buffer size at a confidence level of 75 %                            | 14 m        |                            |
|                                   |   |                                |  | Average zone buffer size at a confidence level of 95 %                            | 28 m        |                            |
|                                   |   |                                |  | Average zone buffer size at a confidence level of 99 %                            | 57 m        |                            |
|                                   |   |                                |  | Maximum zone buffer size at a confidence level of 99 %                            | >=250 m     |                            |
| London OBU Trials, Stage 2 (2006) | 17 OBU's, 14,000 km, 2 weeks                | GPS                            | GPS accuracy                             | Average location error  | 6.7 m       | [TfL, 2006]                |
|                                   |   |                                |  | Minimum position deviation  | 5.1 m       |                            |
|                                   |   | Map-matching                   | Map-matching performance                 | Average of correct identified road segments in case of vendor's own map-matching  | 96.8 %      |                            |
|                                   |   |                                |  | Average of correct identified road segments in case of standard map-matching      | 83.6 %      |                            |
|                                   |   | Charge calculation             | Charge accuracy                          | Average calculation error of the charge in case of vendor's own system            | 6.7 %       |                            |
|                                   |   |                                |  | Average calculation error of trip length in case of vendor's own system           | 5.4 %       |                            |
|                                   |   |                                |  | Average calculation error of the charge in case of standard system                | 11.8 %      |                            |
| London Imperial College -2000     | 1 GPS receiver, 1 car, 1 route              | GPS                            | GPS accuracy, availability and integrity | Percentage of the trip duration with minimum 4 visible satellites                 | 38%         | [Ochieng, 2002]            |
|                                   |   |                                |  | Percentage of the trip duration with minimum 5 visible satellites                 | 15%         |                            |
|                                   |   |                                |  | The total period during which an accuracy demand of 20 m was not met              | 72 min -63% |                            |
|                                   |   |                                |  | Percentage of positions within an accuracy demand of 20 m                         | 99%         |                            |
|                                   |   |                                |  | Maximum continuous period, where an accuracy demand of 20 m was not met           | 4.7 min     |                            |
| London, Imperial College -2002    | 4 GPS receiver 1 car, 1 route               | GPS,                           | GPS accuracy, availability and integrity | Percentage of the trip duration with minimum 4 visible satellites using GPS/DR    | 98%         | [Ochieng, 2003]            |
|                                   |   | DGPS,                          |  | Percentage of the trip duration with minimum 4 visible satellites using GPS alone | 60%         |                            |
|                                   |   | GPS/DR                         |  | Percentage of the trip duration with minimum 5 visible satellites using GPS/DR    | 96.5 %      |                            |
|                                   |   |                                |  | Percentage of the trip duration with minimum 5 visible satellites using GPS alone | 42.5 %      |                            |
|                                   |   |                                |  | The maximum coherent drop-out in the positioning with GPS alone                   | 100 seconds |                            |
|                                   |   |                                |  | Percentage of positions within an accuracy demand of 30 m using GPS alone         | 90-95 %     |                            |
|                                   |   |                                |  | Percentage of positions within an accuracy demand of 30 m using GPS/DR            | 95%         |                            |
|                                   |   |                                |  | Percentage of positions within an accuracy demand of 100 m using GPS/DR           | 100%        |                            |

Table 4.13: Summary of Results - Part 1.

| Study/years                          | Devices/duration  | Technology  | Test purposes                                  | Description  | Results          | Source             |
|--------------------------------------|---|---|--|--|------------------|--------------------|
| London: MapFlow (2007)               | 17 OBU's, 14,000 km, 2 weeks  | GPS, Charge calculation   | Non map-matching algorithms                    | Distance deviation for straight-line method (OBU average)                                  | 113.37%          | [MapFlow, 2007]    |
|                                      |   |   |  | Distance deviation for filtration method (OBU average)                                     | 8.26%            |                    |
|                                      |   |   |  | Distance deviation for the advanced method (OBU average)                                   | 16.98 %          |                    |
|                                      |   |   |  | Distance deviation for TfL's vendor map-matching (OBU average)                             | 3.2 %            |                    |
|                                      |   |   |  | Distance deviation for TfL's own map-matching (OBU average)                                | 0.2 %            |                    |
|                                      |   |   |  | Percentage of charge collections with less than 1 % errors using the straight-line method  | 20.24 %          |                    |
|                                      |   |   |  | Percentage of charge collections with less than 1 % errors using the filtration method     | 17.6 %           |                    |
|                                      |   |   |  | Percentage of charge collections with less than 1 % errors using the advanced method       | 2.45 %           |                    |
| Holland: ARS-KMP (2006)              | 19 cars,  | GPS,<br><br>Odometer  | GPS accuracy, availability, distance deviation | Percentage of the trips' duration without valid GPS positions                              | 2.1 %            | [Zijderhand, 2006] |
|                                      | 2,363 trips   |   |  | Percentage of the trips' duration where GPS points cannot be related to a road map (< 50m) | 2.4 %            |                    |
|                                      | 1 month   |   |  | GPS unavailability   | 13 (+/- 2) %     |                    |
|                                      |   |   |  | Average location error   | 6.2 m            |                    |
|                                      |   |   |  | Average distance deviation   | < 1 %            |                    |
|                                      |   |   |  | Average distance deviation for long trips (> 400 km)                                       | 0.3 %            |                    |
|                                      |   |   |  | Average distance deviation for short trips   | > 1 %            |                    |
|                                      |   |   |  | Total distance deviation for all road categories   | 0.4 (+/- 2.2) %  |                    |
|                                      |   |   |  | Total distance deviation for all 50 km/t road category                                     | 1.6 (+/- 9.2) %  |                    |
|                                      |   |   |  | Total distance deviation for all 120 km/t road category                                    | 0.06 (+/- 1.0) % |                    |
| Singapore: Mitsubishi (2007)         | 1 car   | GPS + DR  | Distance measurement in payments zones         | Maximum errors of calculated distance in dense urban environment                           | 11 m             | [Ohno, 2007]       |
|                                      | Maximum errors of calculated distance in medium dense urban environment |   |  | 9 m  |                  |                    |
|                                      | Maximum errors of calculated distance in dense low urban environment    |   |  | 8 m  |                  |                    |
|                                      | Maximum errors of calculated distance                                   |   |  | < 2 %  |                  |                    |
| Denmark: DTU Transport (2003 + 2008) | 40 cars,  | HSGPS (2008)  | GPS quality, satellite availability            | Percentage of several visible satellites from 2003 to 2008                                 | 27%              | [Nielsen, 2003]    |
|                                      | > 195.000 trips, 10 months  |   |  | Average number of visible satellites in 2008   | 8.03 %           | [Jensen, 2005]     |
|                                      | GPS (2003)  | Percentage of GPS positioning with less than 5 visible satellites in 2003 (GPS) |  | 15.85 %  | [Zabic, 2006]    |                    |
|                                      |   | Percentage of GPS positioning with less than 5 visible satellites in 2008       |  | 1.16 %   | [Zabic, 2009]    |                    |
|                                      |   | Average HDOP in 2008  |  | < 2  |                  |                    |

Table 4.14: Summary of Results - Part 2.





# Technical Road Charging Experiment in Copenhagen

---

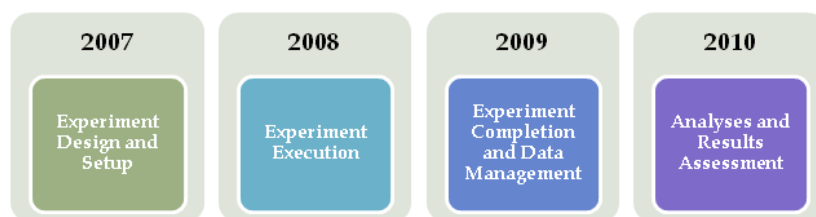
This chapter presents the technical road charging experiment in Copenhagen conducted as a part of the PhD research presented in this thesis. Firstly, the chapter provides a description of the experimental design including the technical and practical experiences during the experiment. As the collected data from the experiment served as the basis for the performance analyses and results presented in this thesis, a data reliability assessment was performed on the collected data set to verify if data was sufficiently complete and error free to be convincing for road charging purpose and context. The data reliability assessment is presented in the second part of this chapter.

## 5.1 Background

The PhD research presented in this thesis is based on an empirical performance study of vehicle location determination in GNSS-

based road charging systems. During 2007-2009, a technical road charging experiment was conducted in Copenhagen as a part of this PhD in cooperation with Siemens. The objective of this experiment was to assess the performance of the vehicle location determination function based on state of the art GNSS-based road charging technology.

In 2007 the experiment was initiated from this PhD research and the experimental design and set-up was hereafter defined in cooperation with Siemens<sup>1</sup> (refer to Figure 5.1). By the end of 2007, the first OBUs were installed in a few vehicles to test the installations and the data transmission.



**Figure 5.1:** Experiment Timescale.

The experiment was conducted in Copenhagen between September 2007 and October 2008. Within this one-year period (400 days), 40 vehicles collected vehicle location determination data with GNSS-based road charging technology developed by Siemens. Figure 5.2 illustrates the experiment set-up. Siemens provided the road charging technology consisting of 40 state-of-the-art OBUs, a back-office solution with web-interface for the participants and support for installation and maintenance during the experiment. TDC mobile provided the GPRS communication for data transmission during the whole experiment. The overall management and coordination of the experiment was conducted within this PhD study.

In order to carry out a realistic assessment of the vehicle location determination performance, the experiment was designed to

<sup>1</sup>Siemens Industrial Solutions & Services Departments: Electronic Toll Solutions in Austria and Power & Transportation in Denmark.

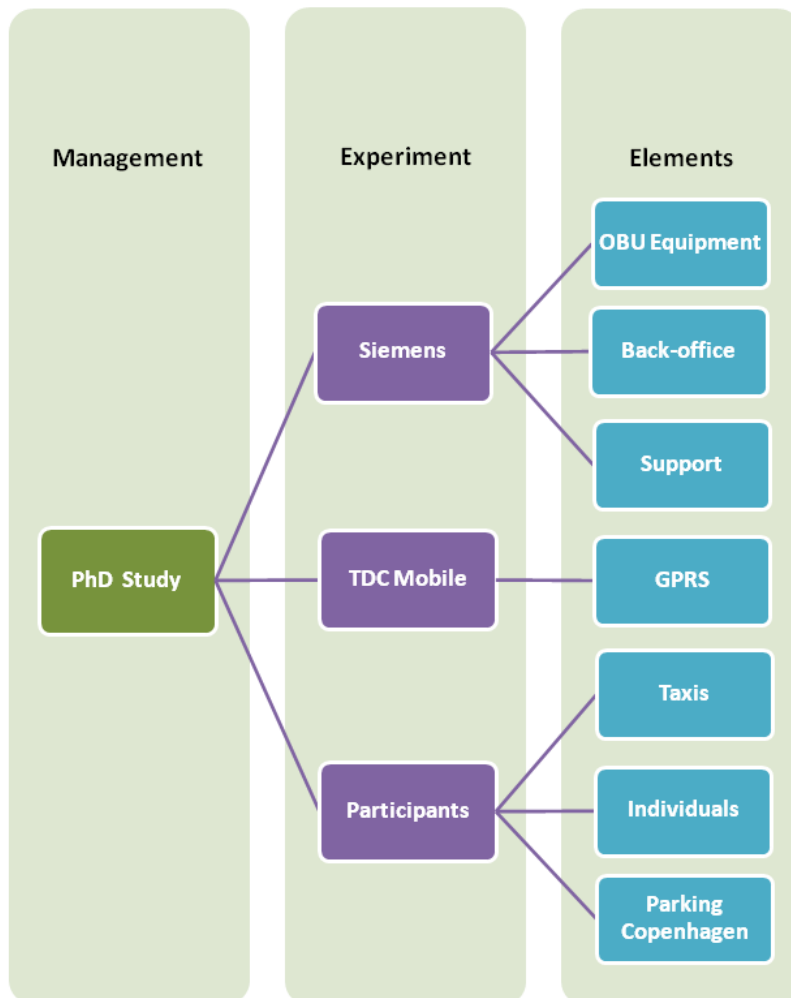
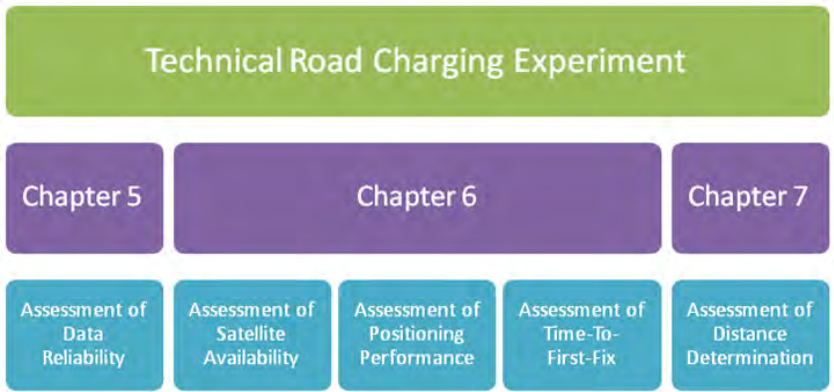


Figure 5.2: Experiment Set-up.

include 40 participants both individuals, taxies and corporate vehicles from Parking Copenhagen, to encompass as many types of conditions as possible. All participants lived and worked in the greater Copenhagen area so that the different spatial urban characteristics were represented.

In 2009, the OBUs were uninstalled and the collected data were handed over from Siemens to DTU Transport. Hereafter, data management was undertaken in order to setup a database server and extract, transform and import the collected data. In the following, this received data set was used in its complete form without any data washing and is referred to as the collected data. Different subsets of this data set are used only when mentioned.

During 2009-2010, different analyses were conducted within this PhD research to assess the performance of the vehicle location determination function. The analyses include a data reliability assessment presented in this chapter, followed by analyses on satellite availability, positioning performance and time-to-first-fix in the following chapter (refer to Figure 5.3). Finally, the driven distance determination performance is assessed based on simulations.



**Figure 5.3:** Performance Assessment Analyses Presented in this Thesis.

All analyses were conducted as a part of this PhD study and the results from these assessments are presented in this thesis.

## 5.2 Experimental design

The vehicles drove 10 months on average and provided 194,047 trips in total (refer to Table 5.1). The total distance travelled<sup>2</sup> for all 40 vehicles during the experiment is 221,784 kilometers. The collected data included more than 48 million GPS observations and provided information on time, date, longitude and latitude, the number of visible satellites, horizontal dilution of precision (HDOP), mileage and velocity.

The OBUs (smart clients) used a latest generation high sensitivity GPS-receiver with an internal antenna. All GPS positions were measured and logged with a 1Hz frequency and sent to a back-office system approximately every 30 minutes by GSM communication. The OBU GPS receiver specifications can be found in Table 5.2.

| Data Characteristics          |                          |
|-------------------------------|--------------------------|
| Total number of trips         | 194,047                  |
| Number of vehicles            | 40                       |
| Measurements period           | 27-09-2007 to 31-10-2008 |
| Total number of GPS positions | 48,721,765               |
| Total distance travelled      | 221,784 km               |
| Total time travelled          | 24,713 hours             |
| Total time logged             | 12,996 hours             |

**Table 5.1:** Data Characteristics.

The acquisition time mentioned in the GPS receiver specifications refers to how long it takes to gather signals from enough GPS satellites to determine its location after being switched on. Cold, warm and hot starts refer to when the GPS receiver last was used.

The vehicle location determination data from all 40 vehicles was continuously collected and stored in the Siemens back-office system. By the end of the experiment, data was transferred to DTU Transport as large text-files. The large amount of data was subsequently imported and processed in a MySQL database.

<sup>2</sup>The total distance travelled is based on the OBU mileage measurements.

| Receiver specifications |   |
|-------------------------|---|
| Receiver type           | SiRFstarIII   |
| Frequency               | L1 C/A code   |
| Channels                | 12  |
| Update rate             | 1 Hz  |
| Acquisition times       | Cold start $\leq$ 100 sec<br>Warm start $\leq$ 40 sec<br>Hot start $\leq$ 8 sec |

**Table 5.2:** Receiver Specifications.

In order to lay emphasis on the spatial distribution of the performance parameters, the analyses presented in this thesis were all conducted with the ArcGIS Desktop packages (ArcInfo Desktop, ArcEditor and ArcView) supported by the ArcGIS Extension package Geostatistical Analyst. Furthermore, GME tools for ArcGIS from [Geospatial Modelling Environment, 2010] were used for the assessment analyses. Due to ArcGIS software limitations, different subsets with randomly selected positions were created for the presented analyses of the navigation function performance. A digital map of the Copenhagen road network was used as a geographical reference for the analyses<sup>3</sup>.

When possible, the analysis results were compared to relevant research in order to enhance any differences or improvements from previous results.

### 5.3 Technical Challenges

During the experiment, different technical problems occurred causing both loss of position information and invalid data. In this section, some of these technical challenges are described.

<sup>3</sup>All digital road maps used in relation to this thesis are based on KRAK kdv geodatabase (www.krak.dk).

### 5.3.1 Installation Errors

During the experiment, all installation and maintenance tasks of the OBUs were managed by DK Mobil Center and Siemens. The OBUs were mounted in the lowest right side of the vehicle's windshield and attached to the window either by tape or by four suction disks. Furthermore, the OBU's power cables were connected to the vehicle's power supply.

OBUs are normally placed in the lower part of the windshield to avoid the metal film some vehicles have as sun screen in the topmost part of the window glass as experience show that this may disturb signal reception [Nielsen and Würtz, 2003]. However, during the installation phase it was found that for some newer types of vehicles, this placement was not possible due to design of the airbag release areas. In four of the vehicles (taxies), the OBUs were instead mounted in the back window in order to avoid any risks regarding the safety of passengers. This placement of OBUs did not result in any technical errors.

For some vehicles, the OBU came loose from the window and dangled from the windshield (only held by the power cables) or was put down on the floor in front of the passenger seat until an new appointment was made with the installation staff. During this period, the GPS receiver installed in the OBU might not have logged any position data or logged incorrect positions due to the limited sky visibility. These types of errors may have caused several missing position logs and inaccurate positions in the data set resulting in invalid trip information.

Another problem was that several OBUs switched on and off sporadically when the vehicles were parked. The OBUs were designed to turn on and off along with the vehicle engine, but in several cases OBUs turned on without the engine started, resulting in many trip registrations in the data set with zero mileage. Furthermore, several participants noticed that their OBU often turned on and off during their driving and sometimes had breakdowns for several hours or days and was thereby off during whole trip durations. These types of OBU errors have resulted in unregistered

trips and invalid trip information regarding duration and mileage as both small and large data parts are missing for the off-periods.

### 5.3.2 Communication Errors

The logged data from the OBUs were transmitted to a back-office system approximately every 30 minutes by GSM/GPRS communication provided by TDC. These SIM-cards were integrated in the OBU and the communication worked well during the experiment.

One important factor is that these SIM-cards were delivered unlocked (without PIN-code) and open during the whole experiment duration (expiration date). As the duration of the experiment was extended due to delay of OBU delivery and installations, the corresponding extension of the SIM-cards was however forgotten, which resulted in loss of trip information until re-opened. After re-opening of the SIM-cards, several OBUs were not able to automatically start sending data again.

Another communication problem during the experiment was caused by text messages (SMS). As the Danish and Swedish GSM networks are very close to each other, the integrated mobile communication in the OBUs sometimes changed network when driving along the coast. When changing network between countries, users typically receive a text message welcoming them with information on communication costs. The OBUs were not prepared for these text messages and were therefore out of order until the OBU software got updated, which hence resulted in unregistered trips.

### 5.3.3 Data Overload

The experiment was designed to gather all transmitted vehicle data on a back-office server. However, handling these large amounts of continuously incoming data are a technical challenge and at one point during the experiment the back-office server had a breakdown due to data overload.

Whenever OBUs were not able to transmit any data due to differ-



ent reasons, all logged data is kept locally in the OBUs until their memory limit was reached. Consequently, no more data could be logged due to data overload until the server was repaired.

These types of errors have consequently resulted in missing trip registrations.

#### 5.3.4 Data Processing Errors

The participants had a web account by which they could log in and have a look at their trip information. In road charging systems this function is important for the road users as it enables the possibility of continuous trip verification and thereby helps to ensure the road users' trust in the system. During the experiment, this service was not always available due to the server problems mentioned above and sometimes delayed due to management of the large data amounts.

For the research presented in this thesis, data was delivered as text files. In these files, it was found that several trips had double identical records and in other cases, multiple trips were registered as one. Furthermore, not all trip IDs were unique in the data set.

These types of errors may have been caused by installation or communication errors or may be data processing errors originated from the database.

### 5.4 Other Challenges

During the experiment, different challenges occurred which are important to consider when implementing GNSS-based road charging systems or setting up GNSS-based trials. In this section, some of these challenges are described.

### 5.4.1 Getting Permissions

In Denmark, dispensable objects in the vehicle windshield are not allowed. Therefore it was necessary to get permission from authorities prior to installation of the OBUs. A letter of application was sent to the local police office which later on was declined as the local police did not have the required authority to grant the permission. The Danish Road Safety and Transport Agency granted the permission to install OBUs for research purpose in the 40 vehicles.

In 2000, the Act on Processing of Personal Data entered into force in Denmark. This act ensures the protection of individuals with regard to the processing of personal data and on the free movement of such data. The Danish Data Protection Agency exercises surveillance over processing of data to which the act applies (refer to [[The Danish Data Protection Agency](#)]). Therefore an enquiry was made to The Danish Data Protection Agency to make certain that all processing of personal data was in accordance with the applicable rules. For this experiment, a document was composed in which each participant approved (by signature) the use of his/hers personal data for research purposes. Signatures were required from all participants.

### 5.4.2 Recruiting Participants

Recruiting participants for an experiment or trial is not an easy task. It is therefore important to be aware of the efforts needed in order to get the required number of participants within a specific deadline. Finding the 40 participants for this experiment meant sending requests to more than 500 people using friends, family and network connections. No monetary gains were given to the participants, so it was important to keep them motivated during the experiment and especially during delays and technical problems.

Many participants were concerned about the OBU installation and possible interference with the vehicle electronics. One participant had to withdraw his participation as his new car would lose its

guarantee if any electronic devices were installed by unauthorized car dealer garages. Other concerns included safety of passengers in case of accidents and vehicle damage due to theft of the OBU. In Denmark, it is namely the participant's own insurance that shall cover these damage costs, but luckily no damage happened during the experiment.

## 5.5 Data Reliability Assessment

In the following section, an assessment of the data reliability is presented. Data reliability in this thesis, defines when data are sufficiently complete and error free to be convincing for road charging purpose and context. This does not mean that data are completely error free, but that the errors found are within a tolerable range in relation to ensuring a fair charge. According to [Morgan and Waring, 2004], data are considered reliable when they are:

**Complete:** data include all of the data elements and records needed for the purpose.

**Accurate:** data are consistent, clear and well-defined and reflect the source correctly.

**Unaltered:** data reflect the source and have not been tampered with.

It is important to assess the data reliability as the registered vehicle location determination data forms the basis for the charge construction function (refer to Figure 4.1 on page 85). Due to the different technical problems during the experiment, several data errors exists within the data set both in terms of missing position information and invalid trip information. As these data errors may affect the determination of distance driven in continuous charging schemes, it is therefore important to assess and understand the error occurrences and effects in relation to GNSS-based road charging systems.

The data reliability in this experiment is affected by two overall causes:

- Data invalidity
- Data deficiency

### 5.5.1 Data Invalidity

In this thesis, data invalidity refers to all types of data with invalid information for whatever reason. According to [Morgan and Waring, 2004], data validity refers to whether data actually represent what you think is being measured.

During the experiment several OBUs turned off and on sporadically when the vehicle was parked, which have resulted in 78 % invalid registered trips for which the trip mileage is zero. Whenever the OBUs turned on, trips were registered with zero mileage, but still with durations since the GNSS receivers had logged positions with very low speed. All 40 OBUs in the experiment were affected by this type of data invalidity, but some worse than others. In the data set, approximately 22 % trips exist with a duration  $> 0$  and a trip mileage  $> 0$ .

Figure 5.4 illustrates such an example of invalid trip information. The trip illustrated has no mileage, but the OBU has logged 94,390 GPS positions within a radius of 30–50 meters. The average speed for the illustrated example is 0.093 km/h. The problem related to this type of data invalidity is the amount of incorrect and useless data being transmitted, stored and processed within the system and taking up the system resources. In this illustrated case, almost 100,000 data records exist with a duration of more than 24 hours for a trip that has not been driven.

In general, the on/off switching OBUs have resulted in many trips with short durations and short distances. As the OBUs switched on/off during driving, these short trips do not represent the truth. Figure 5.5 illustrates the cumulative frequency of trips within different duration intervals. The result shows that approximately 78 % of the trips have a duration less than 1 minute. Furthermore,



**Figure 5.4:** Example of Invalid Trip with Zero Mileage.

the data set contains trips with zero duration. In these cases, the GPS has logged positions, but within the exact same timestamp, resulting in zero trip duration. Correspondingly, most of these trips have zero mileage, but the problem becomes crucial for those incorrectly registered trips that have a registered mileage which can possibly result in a charge if not taken further into consideration.

The figure also illustrates that several large trip durations ( $> 1$  day) exist in the data set, which are due to data invalidity because of incorrectly registered trips or data processing faults. Compared to trip durations for Copenhagen based on acknowledged data from the Danish National Travel (TU) Survey [2006–2010, DTU Transport] given in Figure 5.6, the trip durations during this experiment differs significantly. The TU survey only registers trips with duration of 1 minute and up till 24 hours. The average trip duration for vehicles in Copenhagen is 18.9 minutes. Both data sets have approximately 90 % trip durations less than 1 hour, but the many trips with durations less than one minute are not representative; and are due to the technical problems mentioned above.

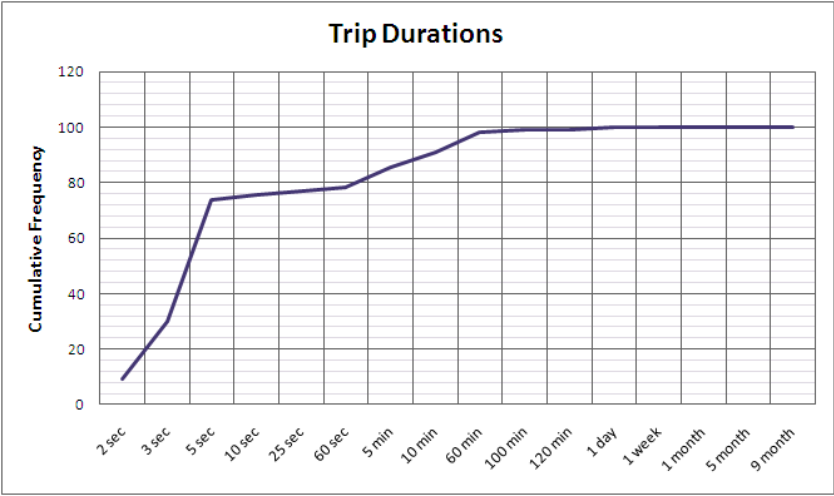


Figure 5.5: Cumulative Frequency of Trip Durations.

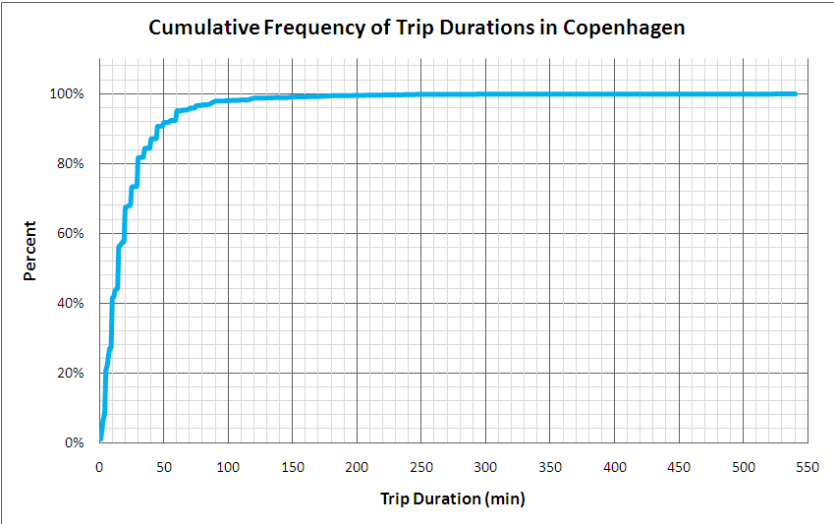
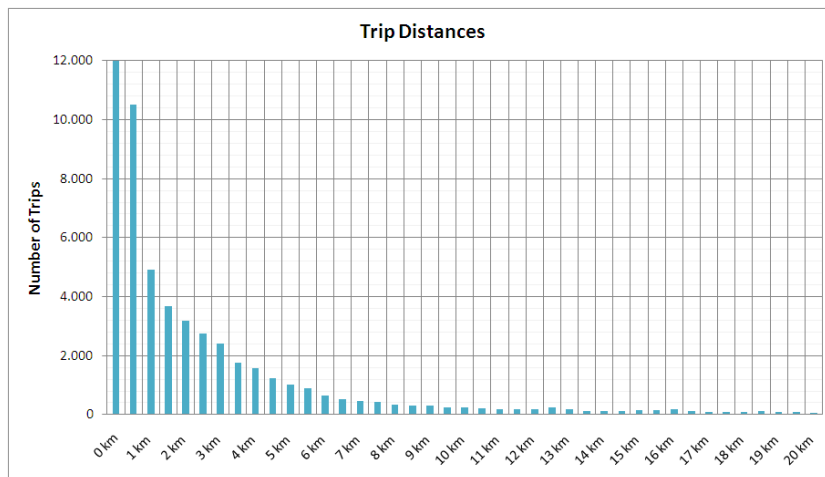


Figure 5.6: Cumulative Frequency of Trip Durations for Copenhagen based on the Danish National Travel Survey.

Figure 5.7 illustrates the distribution of trip mileage<sup>4</sup> within the data set. The results demonstrate that the majority of trips have zero mileage (152,000 trips) and illustrate a large number of short trip distances in general. In addition, 1,882 trips had trip mileage of more than 20 kilometers. The many short trip distances (and durations) in the data set are a consequence of the on/off switching OBUs. However, it should be noticed that both taxi and parking attendant driving also resulted in many short trips due to the many stops.



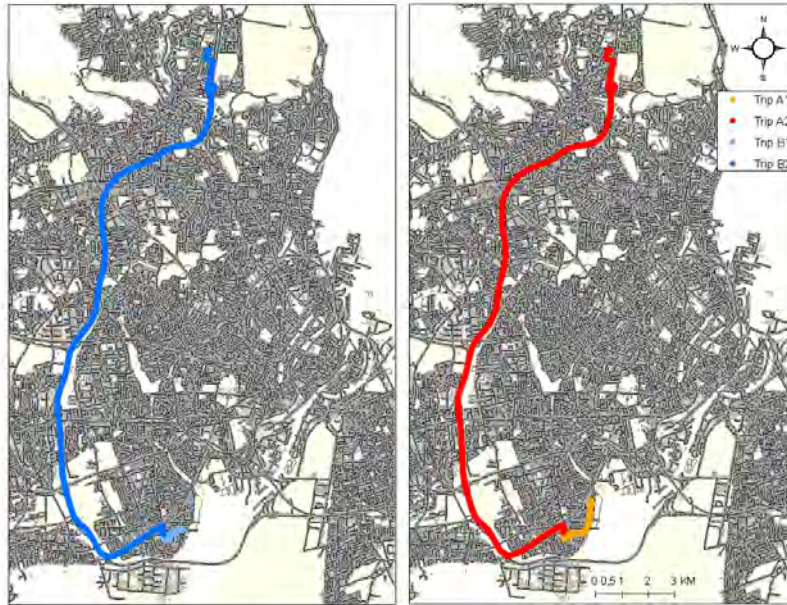
**Figure 5.7:** Distribution of Trip Mileage.

Another example of data invalidity in the data set is incorrect mileage and duration registrations due to several trips being registered as one. The registration may possibly be due to configuration errors in the system set-up or caused by data processing errors in back-office. The problems related to this type of error is the difficulty in separating trips for the charging process. Depending on the system design, these incorrectly registered trips may result in incorrect charging and affect the road users' trust.

Overlapping trips is another challenge within the data set. Overlapping trips refer to two or more trips registered for the same

<sup>4</sup>Based on the OBUs trip mileage determination.

vehicle within the same time period. This is obviously incorrect and may be due to data processing errors resulting in invalid registered date, time or ID information. Examples of overlapping trips are illustrated in Figure 5.8 and supported by trip information in Table 5.4.



**Figure 5.8:** Examples of Overlapping Trips.

| OBU No. | Trip    | Start Time          | End Time            |
|---------|---------|---------------------|---------------------|
| 22      | Trip A1 | 12-03-2008 09:18:58 | 12-03-2008 10:18:57 |
| 22      | Trip A2 | 12-03-2008 09:31:44 | 12-03-2008 10:00:28 |
| 22      | Trip B1 | 17-03-2008 09:13:08 | 17-03-2008 10:17:56 |
| 22      | Trip B2 | 17-03-2008 09:30:49 | 17-03-2008 10:49:37 |

**Table 5.3:** Examples of Overlapping Trips.

The examples illustrate two sets (A and B) of overlapping trips driven by the same vehicle. In both cases, the trips have large gaps of approximately 1 hour during the trips.



Looking more detailed on Trip A1 (refer to Figure 5.9), the data indicate that invalid time information exists. Trip A1 starts (at 9:18:58) in the bottom point of the figure and continues up north along the green points (until 9:20:22). Suddenly, the GPS points jumps (along the red line) to the upper east point (at 10:14:13) and continues south along the purple points, whereafter the trip ends (at 10:18:57) in the same place as the starting point.

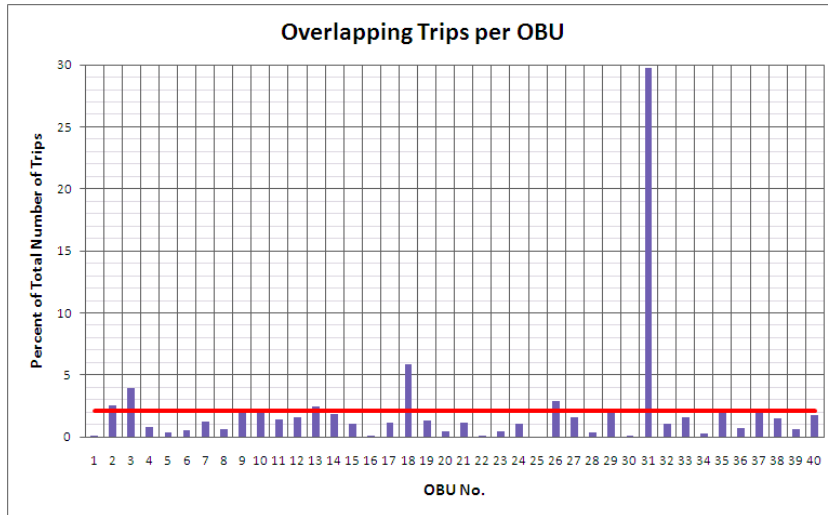


**Figure 5.9:** Trip A1.

From the trip and spatial information illustrated, it seems that the time information in the first (green) part of the trip is registered an hour too early. If the time information in this case is changed from 9 to 10, the trip would be continuous with first the purple part (from 10:14:13 to 10:18:57) and next the green part (from 10:18:58 to 10:20:22). This type of time information failure is probably due to some kind of data processing faults.

The problem related to these overlapping trips is the challenges regarding the road charging process and trip documentation. Ob-

viously, the vehicle must not be charged for two or more trips within the same time period, but the problem is how to identify which trip to charge for and how to document which trip is valid. All vehicles have instances of overlapping trips (refer to Figure 5.10), some worse than others, but approximately 2 % on average. In total, overlapping trips occur 0.9 % in the data set.



**Figure 5.10:** Overlapping Trips per OBU in Percent of Total Number of Trips.

In the original data set, many trips had double registered positions measurements. Double registrations mean that the exact same data record existed twice in data. These double registrations were found both for whole trips and in parts of trips. This type of errors may be due to data processing in the back-office system or configurations problems. In relation to road charging, these double registrations do not affect the determination of distance driven, but may affect the charging process in terms of memory, capacity or speed. The double registrations can be removed from data before the charge construction for instance by use of filtering techniques.

The overall concern regarding the different data invalidity prob-

lems listed in this section is the problems they may cause resulting in incorrect charges, user complaints and data storage problems. The challenge is therefore to consider the handling of these cases, so that automated data processing can replace manual correction work.

The examples of data invalidity errors in the data set are summarized in Table 5.4.

### 5.5.2 Data Deficiency

In this thesis, data deficiency refers to all types of missing information (gaps) in the data set for whatever reason. Table 5.1 shows that only approximately 53 % of the total travel time is logged and represented in data. The reasons for this incomplete data are many. Some of these percentages are the consequence of multiple trips mistakenly being registered as one, which incorrectly indicates large durations of missing data in between trips. Another reason is the OBUs sporadically turning off/on during driving, resulting in loss of data records within trips. In general, GNSS-based data are linked with outages in the positioning data due to different well-known error sources present in especially urban areas (refer to Chapter 4).

In this research gaps are defined as any non-logged position information regardless of its duration. For this data set, a total of 1,242,217 gaps are found with a total duration of 11,717 hours. All 40 OBUs have gaps in their position information, some OBUs worse than others, summing up to 65 % of all trips (refer to Figure 5.11).

Figure 5.12 illustrates the distribution of gaps within different duration intervals. The figure demonstrates that gap durations of two seconds are most frequent in the data set and comprise approximately 90 % of all gaps. It also illustrates that very large gap durations of several days and weeks exists, but these are rare in the data set and make up for a very small percentage (0.3 %) of the total number of gaps.

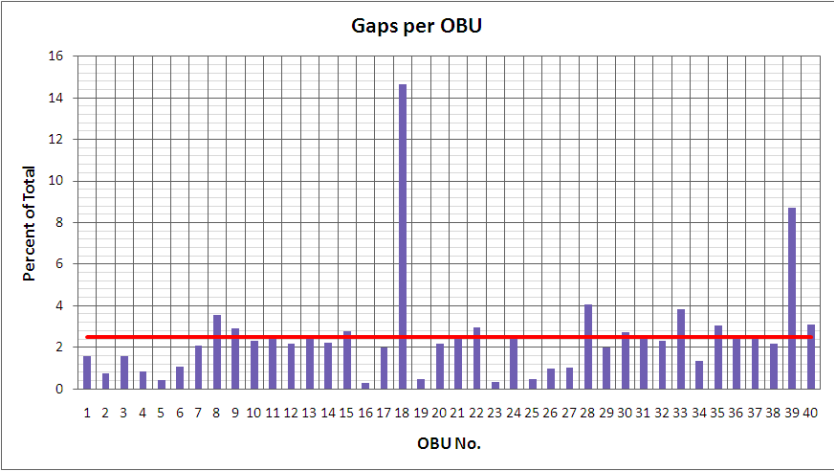


Figure 5.11: Gaps Occurrences per OBU.

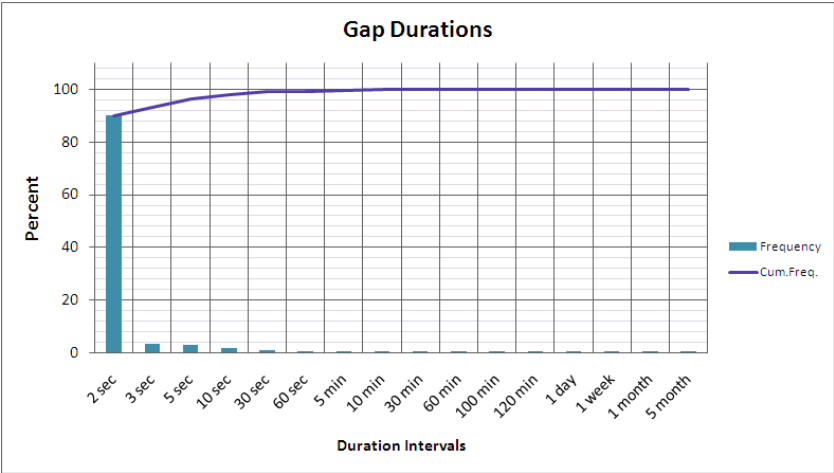
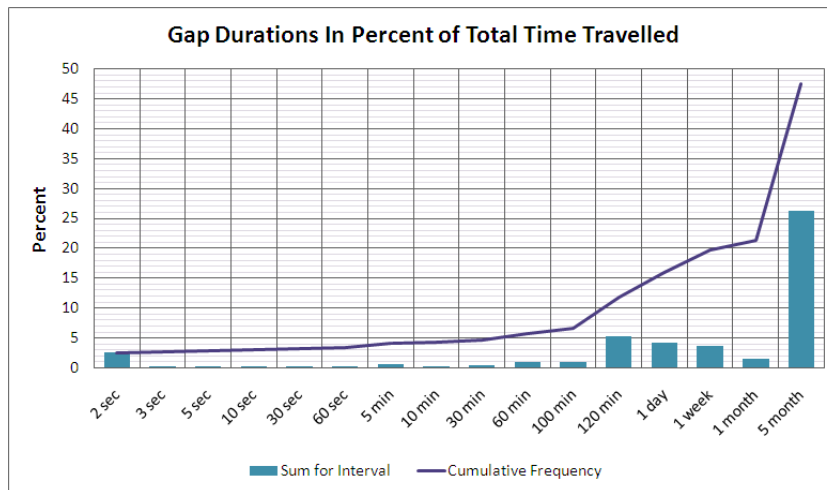


Figure 5.12: Distribution of Gap Durations.

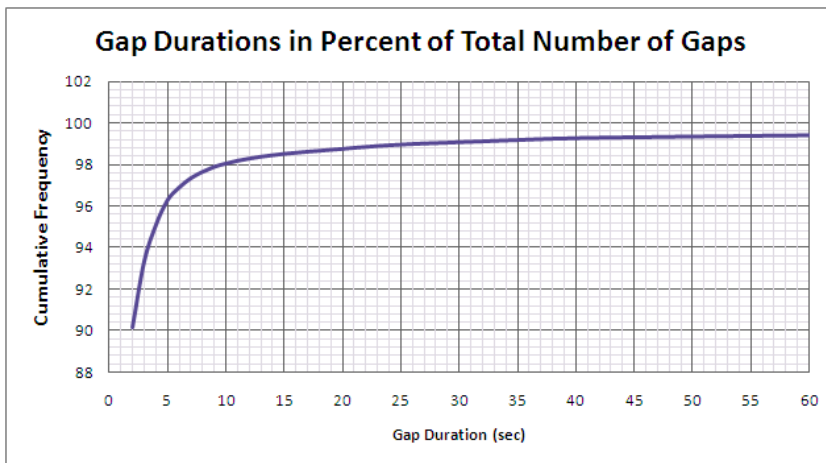


**Figure 5.13:** Gap Durations as Percent of Total Time Travelled.

The data deficiency in this experiment results in approximately 47 % missing information. The cumulative frequency of the gap durations in percent of the total time travelled is given in Figure 5.13. The figure illustrates that the very large gap durations, even though they are rare, constitute a high percentage of the total time travelled. For instance, gap durations larger than one month constitute approximately 26 % of the total time travelled, but only occur three times in the data set. These large gap durations are due to the technical problems mentioned previously, which contribute to a the high level of data deficiency.

The minor gap durations (< 10 min) are more frequent in the data set, but only comprise 4.5 % of the total time travelled. These minor gap durations are apparently caused by the GNSS receiver being unable to estimate positions due to lack of visible satellites. Figure 5.14 illustrates the cumulative frequency of small gap durations (< 1 min) in percent of the total number of gaps. The figure shows that 99 % of all gaps are within 25 seconds.

In Figure 5.15 the frequency of total number of gap occurrences per trip is given. The figure illustrates that while approximately 35 % of all the trips have zero gaps, the majority of trips have

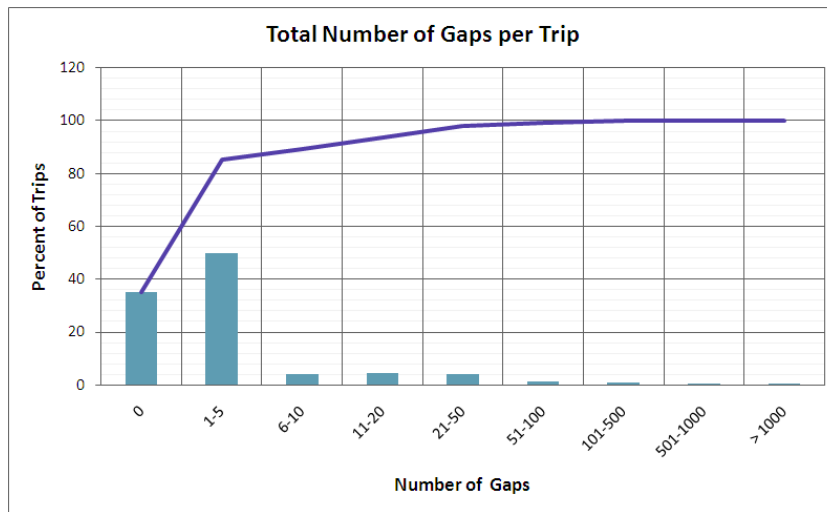


**Figure 5.14:** Cumulative Frequency of Gap Durations less than 1 Minute.

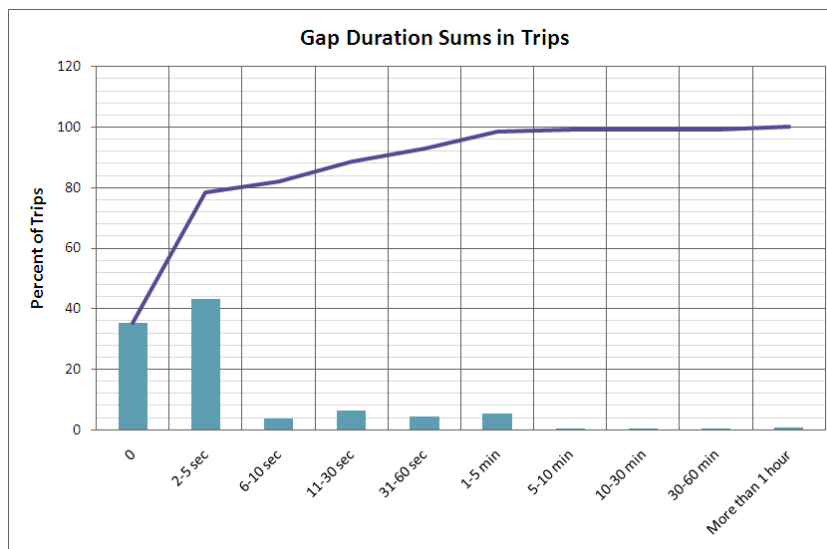
more than one gap occurrence. In this data set, 50 % of all trips have gap occurrences between 1-5 times. Furthermore, the figure shows that approximately 90 % of all trips have zero or less than 10 gaps per trip.

As several gaps can occur per trip, the cumulative frequency of the total gap duration sum per trip is illustrated in Figure 5.16. The figure illustrates that approximately 43% of all trips have a total gap duration sum between 2-5 seconds. Furthermore, it shows that the gap durations for approximately 90 % of all trips sum up to less than 30 seconds per trip.

The distribution of gap durations as percent of total time traveled per vehicle is illustrated in Figure 5.17. The figure illustrates a difference in gap durations between the vehicles, which indicates that some OBUs worked better than others. Furthermore, the figure shows that the gap duration for the best OBUs constituted less than 10 % of the total time traveled, while it constituted more than 70 % for the worst OBUs. Summarized for each vehicle, the duration of gaps constitutes in average 31% of the total time traveled.



**Figure 5.15:** Total Number of Gap Occurrences per Trip.



**Figure 5.16:** Gap Duration Sums per Trip.

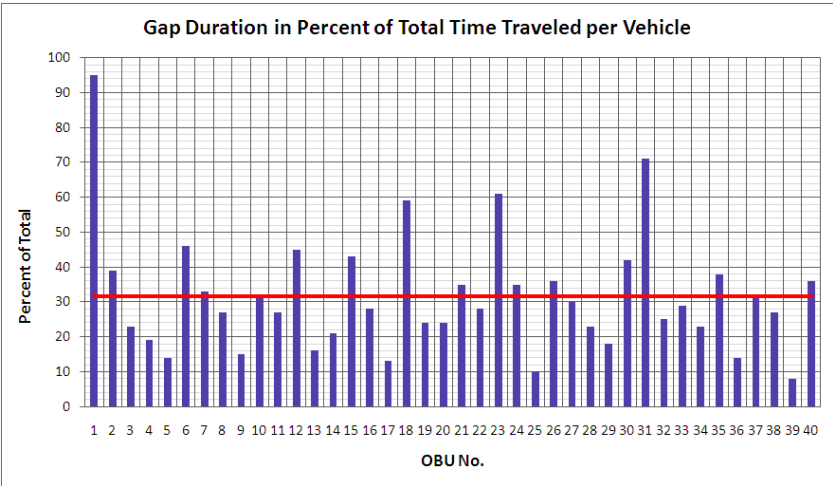


Figure 5.17: Gap Duration per Vehicle.

Figure 5.18–5.21 illustrates the spatial distribution of all the occurred gaps during the experiment, whatever the cause. The result shows that gap durations of more than 60 seconds are clustered in the densest parts of Copenhagen. The smallest gap durations (< 1 min) have occurred in most parts of Copenhagen. Furthermore the results show that several large gap durations of more than one day have occurred in the same place in central Copenhagen, which is the parking area for the corporate vehicles from Parking Copenhagen. These large gap durations are due to technical problems during installation.

Within continuous road charging schemes, these different gaps reduce the possibility of charging road users correctly for their road usage. While minor gaps individually may be negligible in relation to determination of the distance driven, they occur very frequently and can therefore affect the charge construction. On the other hand, large gaps occur rarely but can have a huge impact on the distance determination in the charging process.

The examples of data deficiency errors in the data set are summarized in Table 5.4.



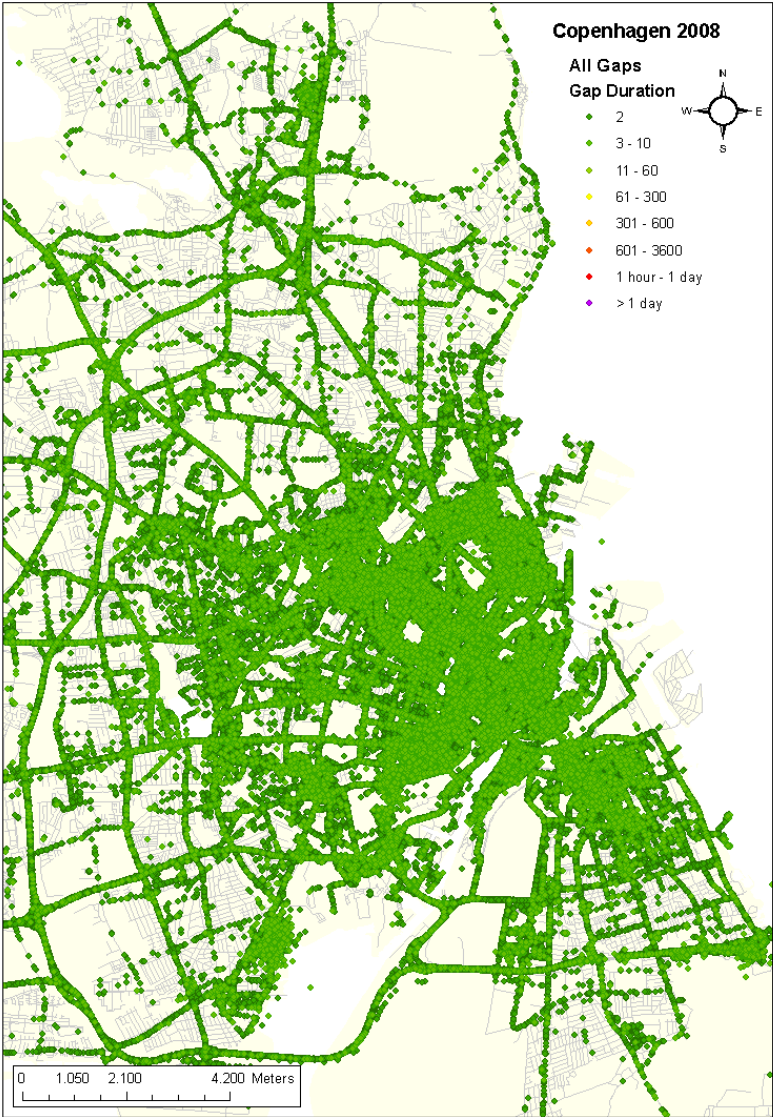
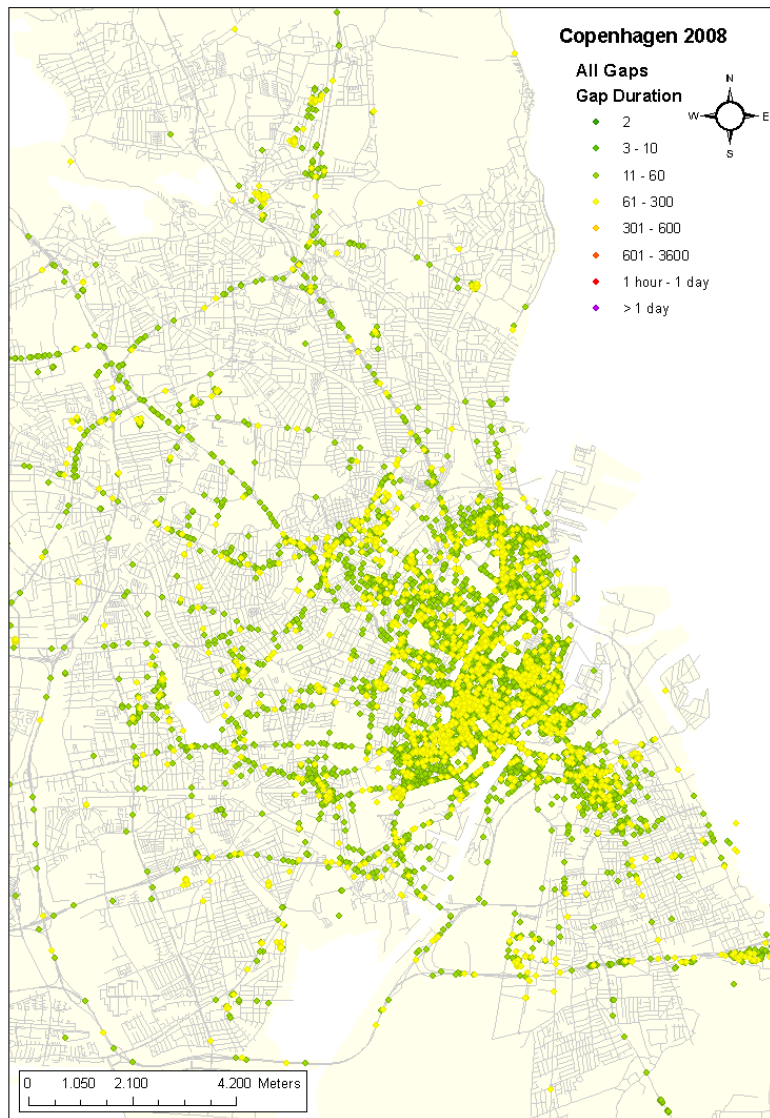
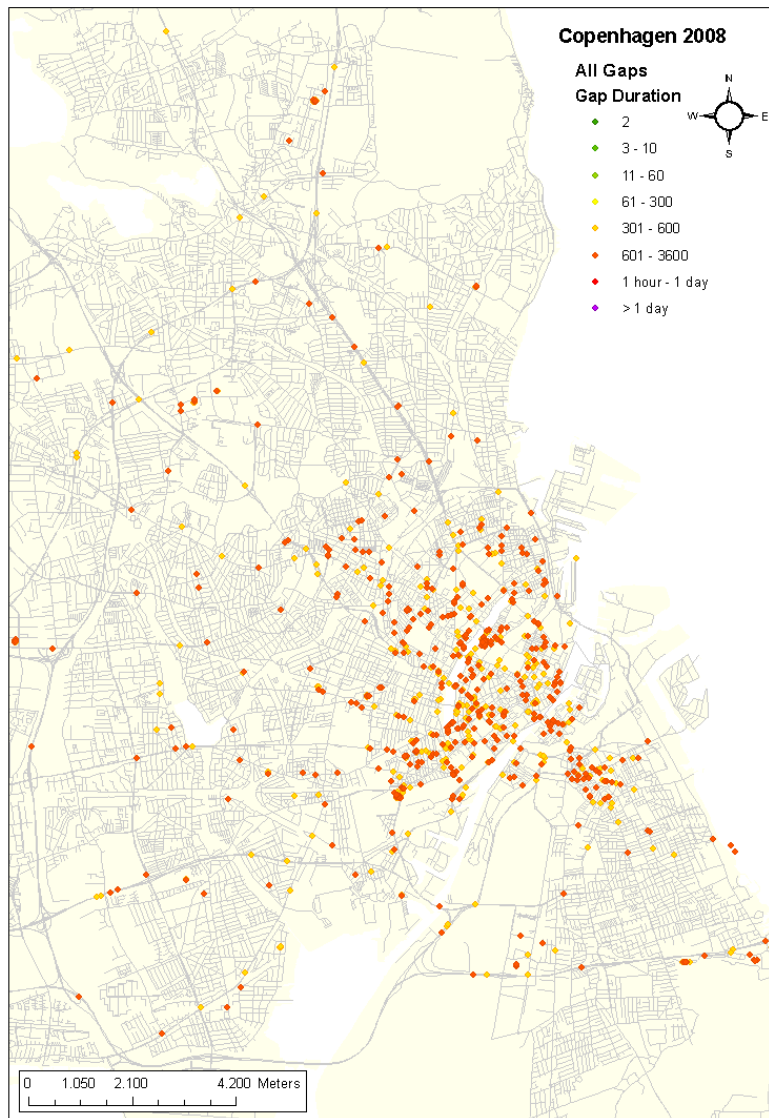


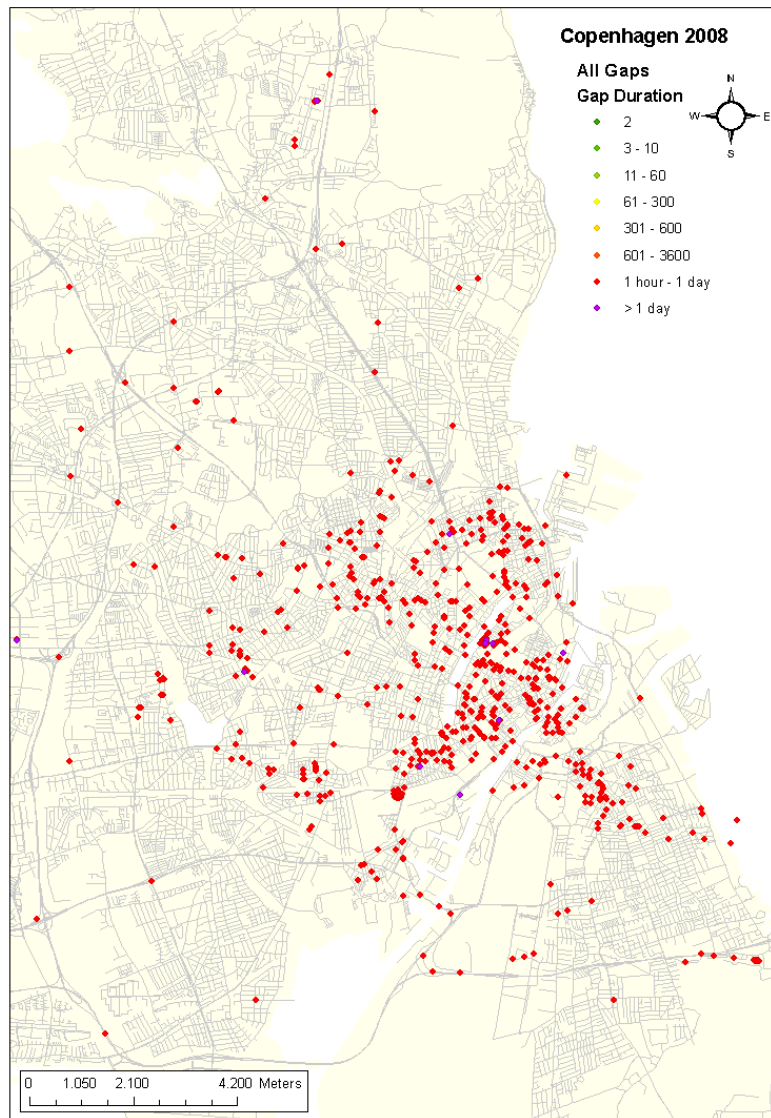
Figure 5.18: Gaps  $\leq 10$  seconds.



**Figure 5.19:** Gaps  $\geq 11$  and  $\leq 300$  seconds.



**Figure 5.20:** Gaps > 5 min and < 1 hour.



**Figure 5.21:** Gaps > 1 hour.

### 5.5.3 Discussion on Data Reliability

In this section, the data reliability has been assessed in relation to being complete, accurate and unaltered for the purpose of road charging. Data reliability is important for any findings and conclusions based on collected road charging data, in order to ensure fair charging in road charging systems.

Due to technical problems during the experiment, the results from this assessment showed that the data reliability in this research was affected by to overall causes: invalidity and deficiency.

The data invalidity was mainly due to the on/off switching of the OBUs, which for many trips resulted in invalid data that do not represent the intended measurements. But also configurations and installation problems resulted in incorrectly registered data. The results showed that the invalidity problems are important to consider in the design of a road charging system as the problems may result in incorrect charges, user complaints and data memory and capacity problems. The challenge is therefore to prevent the technical problems and consider the handling of these data invalidity cases, so that automated data processing can replace manual correction work.

The data reliability assessment showed a high level of data deficiency (47 %) in the data set. This high level is caused by a majority of minor gap durations and several very large gap durations presumably caused by GPS outages and configurations problems respectively. The data deficiency in this experiment resulted in approximately 47 % missing positioning information. The results showed that all 40 vehicles suffer from data deficiency although the level of data deficiency differs between the OBUs. This indicates the challenges of providing the same level of reliability for all road users although the OBUs are from the same production, produced by the same manufacturer. On average, the data deficiency per OBU is 31 %.

The frequency of data reliability problems in the data set are summarized in Table 5.4.

| Error type                                | Frequency     |
|---|---------------|
| Trip with no duration                     | Less frequent |
| Trip with no mileage                      | Very frequent |
| Double registered positions measurements  | Frequent      |
| Multiple registered trips as one          | Frequent      |
| Large gap durations ( $> 1$ day) in trips | Less frequent |
| Gap durations ( $< 1$ hour) in trips      | Frequent      |
| Minor gap durations ( $< 1$ min) in trips | Very frequent |
| Short trip durations ( $< 10$ min)        | Very frequent |
| Large trip durations ( $> 1$ week)        | Less frequent |
| Overlapping trips                         | Less frequent |
| Gaps in positioning                       | Very frequent |

**Table 5.4:** Frequency of Different Error Types in Data.

Based on the presented results, data are found to be unreliable in its existing form for road charging purpose. The data include both inaccurate and incomplete data information, which can have severe impact on the road charging system performance. With these high levels of data invalidity and data deficiency, data can not be used in its current form as the basis for a road charging process. The results highlight the importance of a data processing functionality prior to the road charge calculation and usage determination.

Consequently, it is important to assess and understand the characteristics of the errors influencing the data reliability. In the following chapter, an assessment of the vehicle location determination function performance is conducted in order to determine this function's error contributions to the data reliability in GNSS-based road charging systems.

## 5.6 Summary

This chapter has presented the design and execution of the technical road charging experiment conducted in Copenhagen as part of this PhD research. There are several findings from this chapter.

Firstly, the chapter has provided a description of the technical and practical challenges and experiences during the experiment, which can provide valuable input for future GNSS-based trials or systems. Next, a data reliability assessment was performed on the collected data set to verify if data was sufficiently complete and error free to be convincing for road charging purpose and context. The data reliability was based on an assessment methodology developed for this thesis. Based on the presented results, data was found to be unreliable in its existing form for road charging purpose. The data included both inaccurate and incomplete data information, which can have severe impact on the road charging system performance. Furthermore, the results highlighted the importance of a data processing functionality prior to the road charge calculation and usage determination.





## CHAPTER 6

# Performance Assessment of Vehicle Location Determination

---

This Chapter presents a performance assessment of the vehicle location determination function for GNSS-based road charging systems. Based on experimental work carried out in Copenhagen, this chapter provides different analyses of the vehicle location determination function based on both existing and new methodologies.

In the literature, the use of GNSS to determine continuous vehicle locations has been linked with questions on positioning performance for both road charging systems and other ITS applications. As the data reliability assessment in the previous chapter showed a high level of data deficiency, this chapter analyses the vehicle location determination function in order to assess the GNSS positioning function's contribution to the data deficiency.

First, the satellite availability in Copenhagen is analysed to assess if the prerequisites for GNSS-based road charging are met. The satellite availability in Copenhagen is analyzed and compared to

previous research. Next, the GPS positioning performance is assessed based on the required navigation performance parameters for land applications. In here, the main focus is kept on the positioning continuity which to the author's knowledge is not treated in existing literature. The positioning continuity is particularly important in relation to continuous road charging schemes as the charge is determined on the basis of continuous location determination. Therefore, also the Time To First Fix is considered as one of the main concerns regarding the use of GNSS for road charging systems. This chapter provides a thorough analysis of both the Time To First Fix and the corresponding Distance To First Fix to assess whether in fact these parameters comprise a severe problem.

The results of these assessments are discussed at the end of each section and summarized in an overall discussion of the vehicle location determination performance at the end of the chapter.

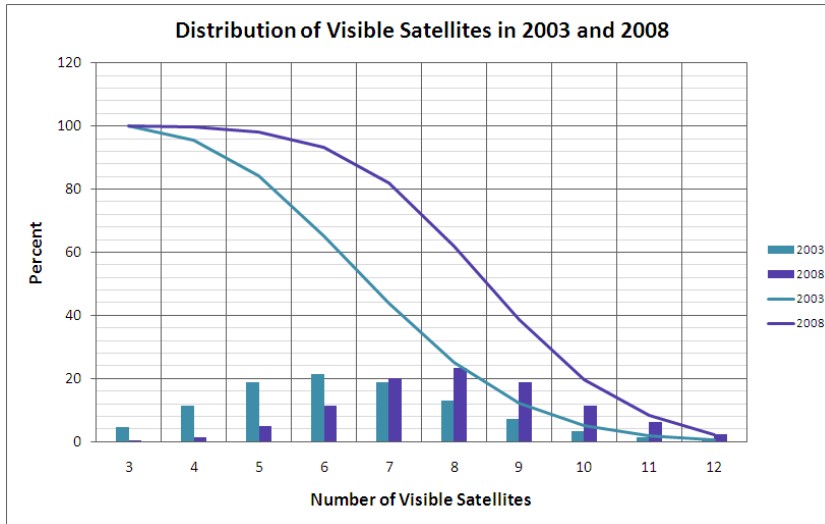
## 6.1 Satellite Availability in Copenhagen

This section analyzes the overall satellite availability in Copenhagen. The satellite availability is an important prerequisite for GNSS-based vehicle location determination, as the required minimum number of satellites must be available to locate the vehicle's positions. This availability assessment addresses the subjects of satellite visibility and positioning quality based on a random subset of the position data. The methodology for the assessment presented in this section is developed based on [Zabic, 2004].

The results from this assessment are compared with previous research of satellite availability based on the AKTA experiment from 2003 (refer to section 4.5.6). The comparison is conducted to re-evaluate the GPS performance in a Danish environment and thereby assess the level of performance improvement obtainable after five years. The analyses and results are presented in the following sections.

### 6.1.1 Satellite Visibility

In the first part of this study, the satellite visibility is analyzed based on a randomly selected subset of data. The satellite visibility statistics (assuming that all satellites are in good technical working order) are shown in Figure 6.1.

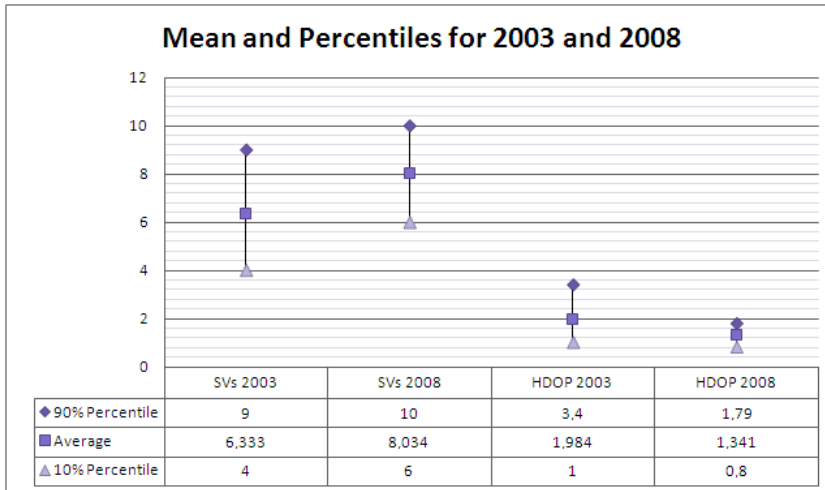


**Figure 6.1:** Distribution of Visible Satellites in 2003 and 2008.

The results show a normal distribution of visible satellites in Copenhagen (2008) with a mean of 8.035. The complementary cumulative distribution function illustrates that the availability of at least four satellites needed for positioning is 99.5 % in the data set. Compared with 2003, for which the distribution is right-skewed, the results show that a higher number of visible satellites were available for positioning in 2008. GPS positioning with less than five satellites have, expressed in percents, decreased from 15.85 % to 1.16 %. The availability of at least four satellites in 2003 was approximately 95.5 %.

The mean values and percentiles of the distributions are given in Figure 6.2. The results show that the mean value for the number of visible satellites (SVs) has increased 27 % from 6.33 in 2003 to

8.03 in 2008, while the deviation at the same time has lowered. The statistics reveals a significant improvement in the satellite visibility from 2003 to 2008. The HDOP figures are analyzed in Section 6.1.2.



**Figure 6.2:** Mean Values and Percentiles for 2003 and 2008 [Zabic, 2009].

While the statistics indicate good satellite visibility in general, one must remember that with road charging in mind, the problem cases of GPS positioning have to be identified in order to provide a reliable charging system. The critical GPS positioning (i.e. positions estimated with less than four satellites) is therefore illustrated in Figure 6.3 on page 168 [Zabic, 2009]. The figure shows the spatial distribution of satellite visibility in Copenhagen. Figure 6.3(b) shows that only 0.16 % GPS positions in 2008 are estimated with less than four satellites and these are clustered in the densest part of Copenhagen. Previous research has demonstrated that the GPS performance in Copenhagen depends on the density of the built-up areas ([Nielsen and Würtz, 2003], [Zabic and Nielsen, 2006]). Hence, the critical positioning areas in 2008 were also found in the most closely built-up neighbourhoods of Copenhagen. Compared with 2003 in Figure 6.3(a), the results indicate significant

improvement in the satellite visibility during the five years from 2003 to 2008. In 2003, there was 4.46 % GPS positions that were estimated with less than four satellites and these fixes occurred in most of the Copenhagen city centre.

The satellite visibility assessment was also examined through a proximity analysis to determine the relationship between GPS positions and the road elements [Zabic, 2006] to examine where the GPS service is usable in the Copenhagen area. By identifying the GPS variables within a 30 meters distance of every road in the Copenhagen area, the average number of visible satellites was estimated per road segment. The result is illustrated in Figure 6.4 on page 169 and compared to AKTA data from 2003. The figure illustrates the difference between the satellite visibility in Copenhagen for 2003 and 2008.

In 2003 (Figure 6.4(a)), GPS positions with an average between three and four visible satellites were found in many streets in central Copenhagen. The study based on AKTA data from 2003 showed that the signal fallouts were primarily found in smaller sideroads. The AKTA analysis revealed that there were streets in Copenhagen where GPS based road charging was not feasible because of insufficient satellite availability (refer to [Zabic and Nielsen, 2006] for the full analysis).

In 2008 (Figure 6.4(b)), the satellite visibility had increased significantly. Most of the road network in Copenhagen has an average number of visible satellites between six and seven satellites and only very few roads have an average less than four visible satellites. In addition, several more roads had a high average between ten and twelve visible satellites in 2008 compared to 2003.

### 6.1.2 Receiver-Satellite Geometry

In the second part of this study, the positioning quality is analyzed. A sufficient number of visible satellites alone is not enough for an acceptable position solution. A good receiver-satellite geometry is also important, and the dilution of precision (DOP) is an easy mean for evaluating the geometry based on the satellite and

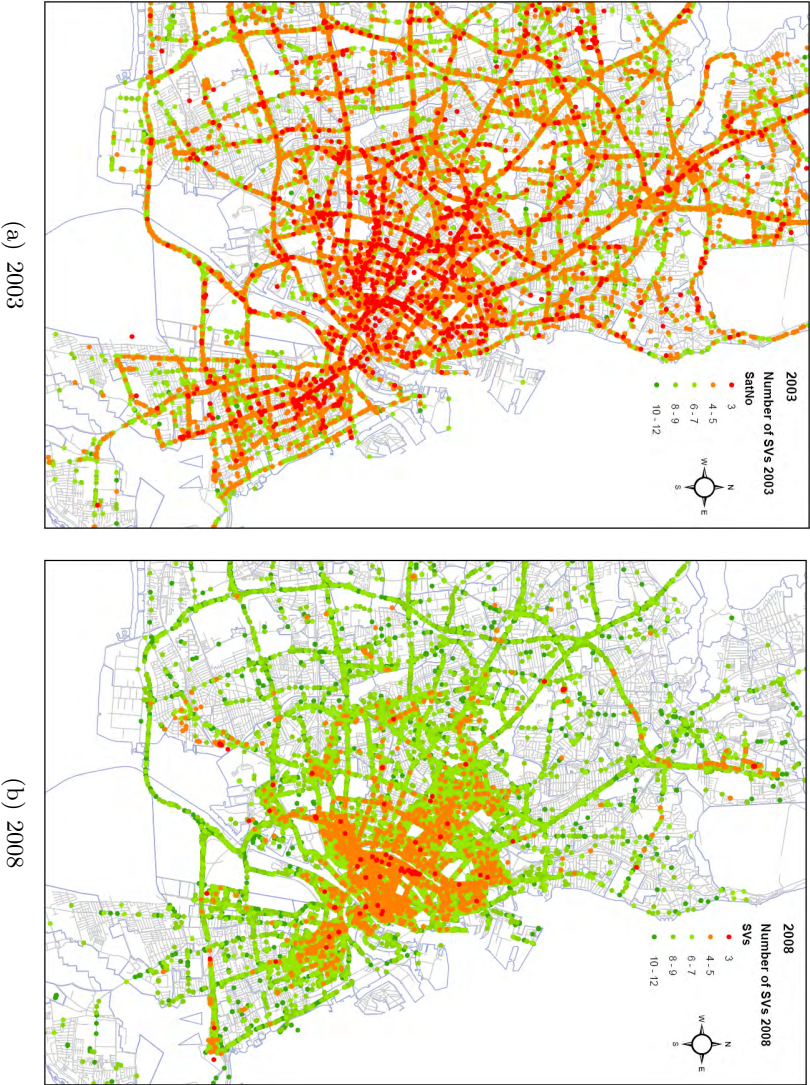


Figure 6.3: Spatial Distribution of Visible Satellites in 2003 and 2008.



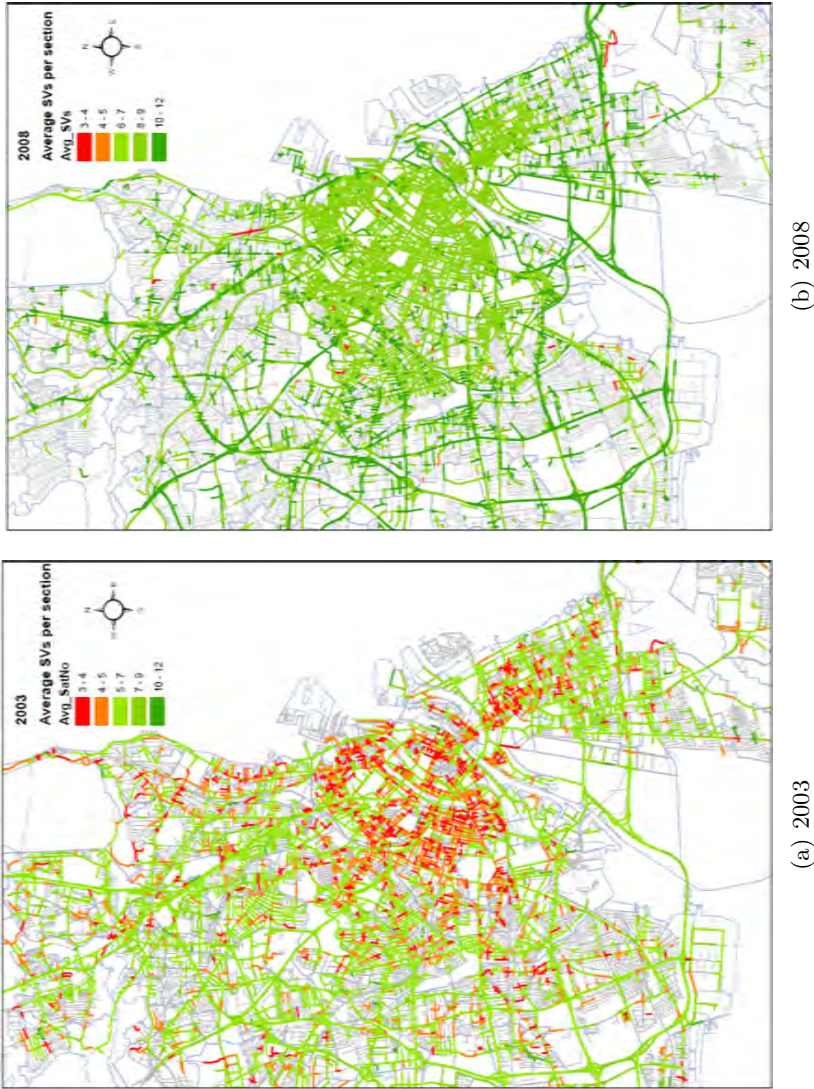
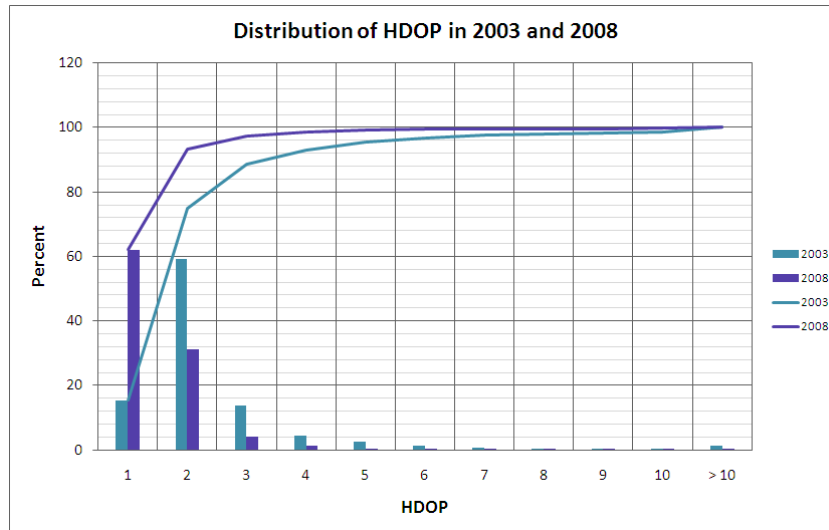


Figure 6.4: Spatial Distribution of Visible Satellites per Road Section in 2003 and 2008.

receiver positions. In this research, the focus is on the horizontal HDOP, since the quality of the horizontal position is of most importance in connection with road charging systems.



**Figure 6.5:** Distribution of HDOP in 2003 and 2008.

Figure 6.6 illustrates the distribution of HDOP in 2003 and 2008. The figure shows that the HDOP decreased from 2003 to 2008 and that the frequency of lower HDOP values had increased significantly. In 2008, approximately 93 % of the position measurements had a HDOP value less than two, while only 75 % of the position measurements had a HDOP value less than two in 2003. Figure 6.2 on page 166 shows a comparison of HDOP mean and percentiles values for 2003 and 2008. During the five years, the HDOP mean decreased 48 % from 1.98 in 2003 to 1.34 in 2008 and the deviation in 2008 was significantly lower.

The spatial distribution of HDOP is illustrated in Figure 6.6 on page 172. The results show that the horizontal position quality in 2008 (Figure 6.6(b)) had improved for the majority part of the Copenhagen area. The HDOP values greater than two were clustered in the city centre. In 2003 (Figure 6.6(a)), several more high HDOP values existed. The HDOP values greater than two were



very disperse throughout the whole Copenhagen area.

In 2005, a Galileo Simulator was developed to simulate the anticipated satellite visibility and positioning quality in Copenhagen with the upcoming Galileo system (refer to [Jensen et al., 2005]). For a small part of downtown Copenhagen, the average HDOP was estimated derived from a proximity analysis with ArcGIS based on AKTA data from 2003. For the same part of Copenhagen, a proximity analysis has been conducted with 2008 data, to reassess the horizontal position quality. The HDOP comparison is illustrated in Figure 6.7 on page 173. The scaling was based on own experience with GPS positioning, as the position accuracy generally is good when the HDOP is lower than two. Theoretically, according to [Misra and Enge, 2006], the 99 % percentile of the HDOP is 1.6 considering the full GPS constellation on a global basis, and no obstructions.

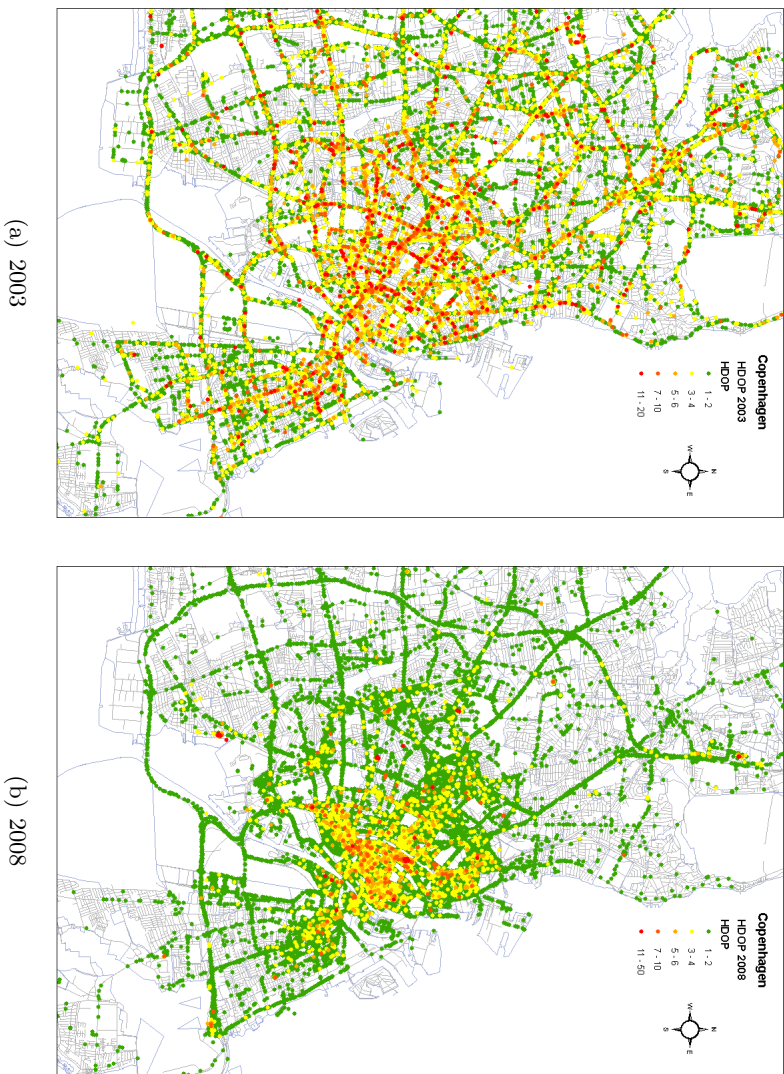
The results show that the average HDOP in 2008 is less than two for a great part of the downtown area. No roads in the downtown area have an average HDOP above three. In 2003, the situation was different with several roads which had an average HDOP value above three. The results show a major improvement in the positioning quality and hence computation accuracy, which is important for the charging accuracy of a road charging system.

### 6.1.3 Discussion on Satellite Availability

The GPS availability in Copenhagen has been analyzed in this section based on satellite visibility and positioning quality. The satellite availability is an important prerequisite for GNSS-based vehicle location determination, as the required minimum number of satellites must be available to locate the vehicle's positions.

The results of this assessment show that the satellite visibility has improved significantly in Copenhagen. The mean for the number of visible satellites increased by 27 %, while the deviation at the same time has lowered. Furthermore, GPS positioning with less than five satellites decreased from 15.9 % to 1.7 %. During the five years, the HDOP mean decreased by 48% from 1.98 in 2003 to

Figure 6.6: Spatial Distribution of Horizontal Position Quality (HDOP) in 2003 and 2008.



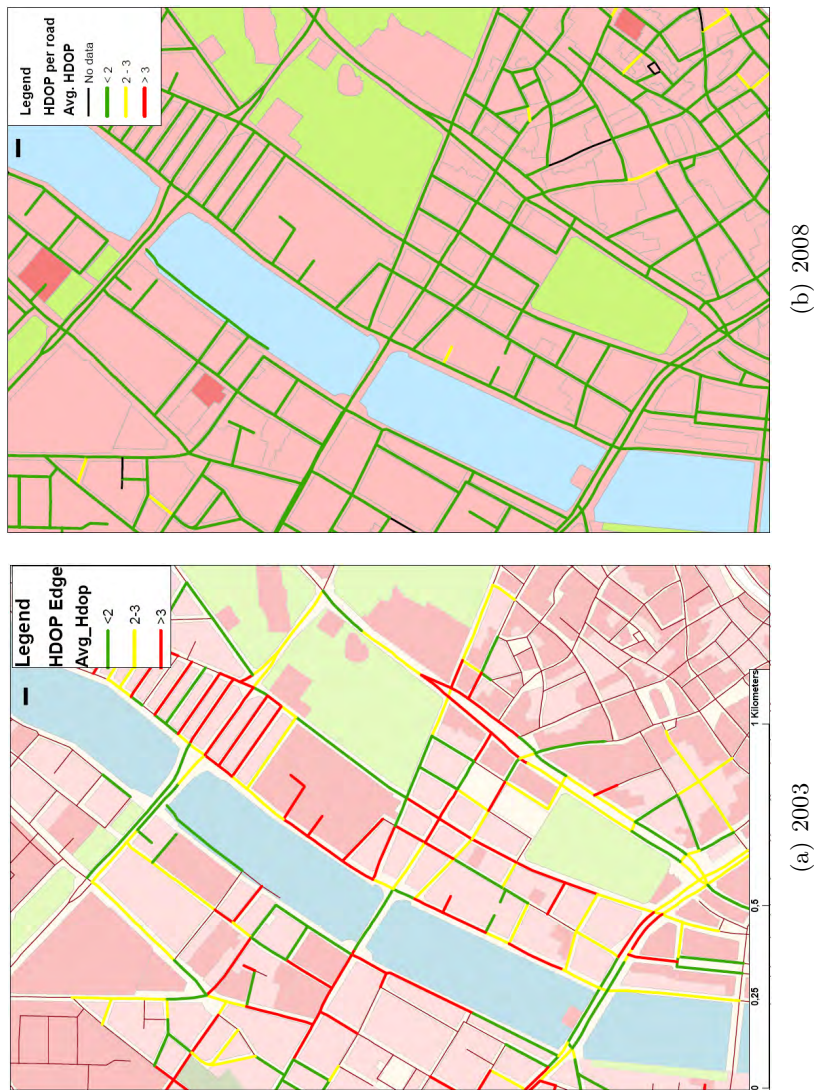


Figure 6.7: Average HDOP per Road Segment in Downtown Copenhagen (Nørrevold Area) in 2003 and 2008.

1.34 in 2008 and the deviation in 2008 is significantly lower. The HDOP in 2008 is less than two in 91 %.

The results show a major improvement in the positioning quality and hence computation accuracy, which is important for the charging accuracy of a road charging system. Based on comparisons with results from previous trials in Copenhagen, the assessment results indicate improved GPS availability in 2008. Due to improved receiver technologies and an ongoing modernization of the GPS system, a better satellite visibility and positioning quality is obtained in 2008. In addition, the number of active broadcasting GPS satellites increased from 28 satellites in 2003 to 31 in 2008 [NGA GPS Division, 2010].

Compared with the previous results from 2003, the analyses show that major improvements in the satellite availability have happened during the five years from 2003 to 2008 and that the prerequisites for GNSS-based vehicle location determination in Copenhagen were present in 2008.

The satellite visibility results have exposed some important characteristics, which can be considered in the process of designing a road charging system in Copenhagen. Although the satellite visibility in Copenhagen has improved significantly, the results show that there are still streets in the city centre where the satellite visibility will be limited. Hence, the spatial study of the satellite availability will provide useful information for the design of augmentations to the primary positioning system in the Copenhagen environment.

## 6.2 Assessment of Required Navigation Performance

In this section, the GNSS performance is assessed on the basis of the required navigation performance (RNP) parameters for land applications (refer to section 4). The performance assessment presented in this section addresses the subjects of positioning availability, accuracy, integrity and continuity.

In this section, the main focus is kept on the positioning continuity which to the author's knowledge is not treated in existing literature. The positioning continuity is particularly important in relation to continuous road charging schemes as the charge is determined on the basis of continuous location determination. Due to the high level of data invalidity, a subset of valid trip data are selected for the following analyses. The subset consists of 1,000 random selected trips for which duration and mileage is greater than zero; and the average speed for each trip is greater than 5 km/h. The subset represents all OBUs during the entire measurement period. The subset characteristics are given in Table 6.1.

| Data subset: 1,000 trips      |                          |
|-------------------------------|--------------------------|
| Total number of trips         | 1,000                    |
| Number of vehicles            | 40                       |
| Measurements period           | 07-11-2007 to 29-10-2008 |
| Total number of GPS positions | 802,257                  |
| Total distance travelled      | 6,134 km                 |
| Total time travelled          | 268 hours                |
| Total time logged             | 222 hours                |

**Table 6.1:** Data Characteristics for the Subset.

The spatial coverage of the position measurements and the occurred gaps for the 1,000 trips data set is illustrated in Figure 6.8. The spatial distribution is layered with the gaps layer on top.

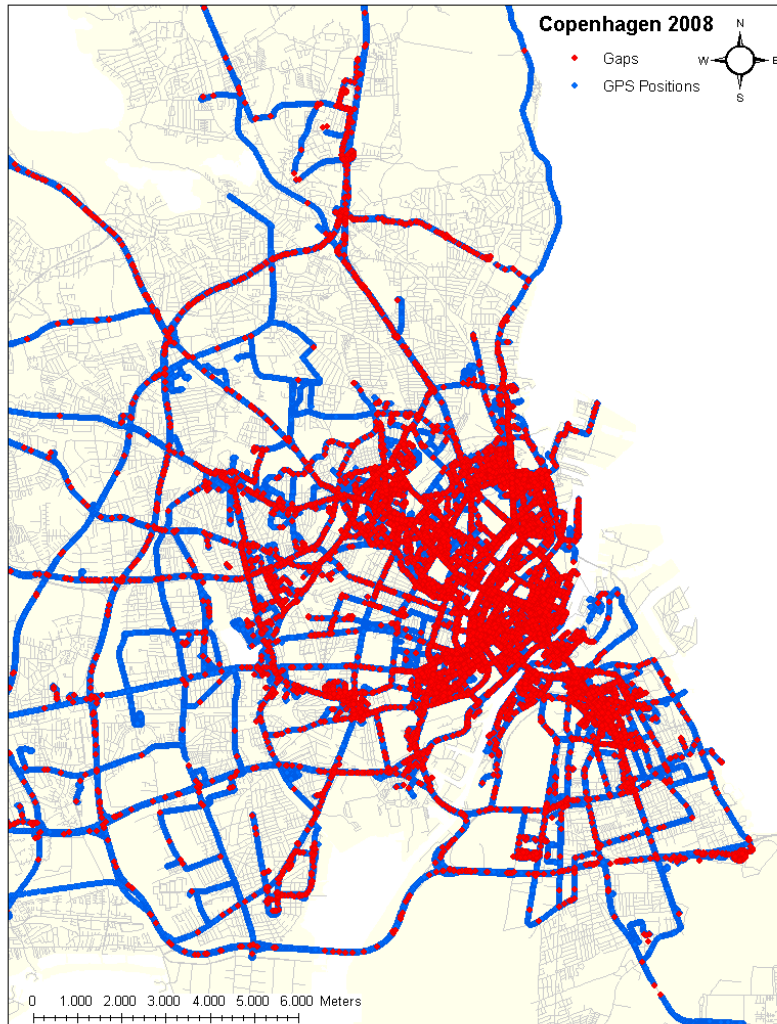
The analyses and results are presented in the following sections.

### 6.2.1 Positioning Availability

Positioning service availability describes the percentage of time the GNSS service is available for use, without outages, whatever the cause (refer to section 4.3.4).

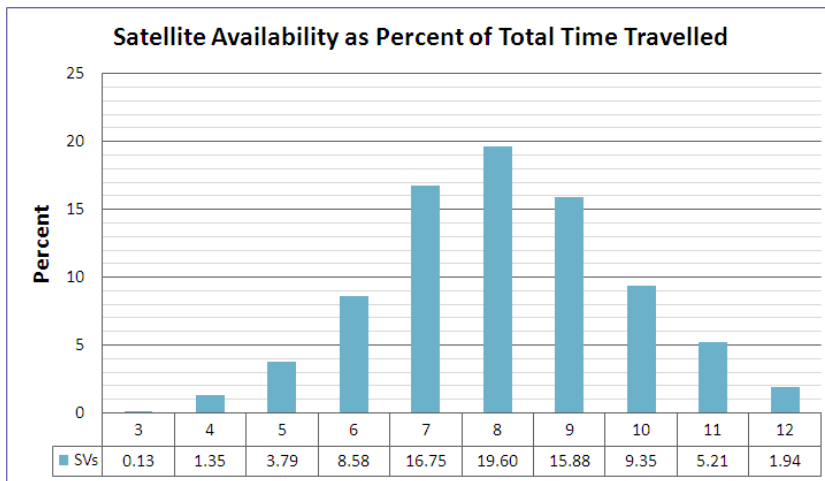
According to [Ochieng et al., 2003a], the availability of positioning measurements is expressed by satellite availability as a percentage of the mission duration (e.g. total time travelled). As the GPS





**Figure 6.8:** Coverage of 1,000 Trips and Gaps.

receiver, in this experiment, is integrated in the OBU, the unavailability of the positioning service during the total time travelled also has other non-GNSS related causes as seen from the data reliability assessment. The results from this assessment of positioning service availability are therefore supported by the results from the overall assessment of satellite visibility in the previous section. The satellite availability is assessed as percentage of the trip durations based on the subset consisting of 1,000 trips. The result is illustrated in Figure 6.9.



**Figure 6.9:** Satellite Availability as Percent of Total Time Travelled.

The result shows that the availability of a least four satellites is approximately 82.5 % during the total time travelled. While the required four satellites in general are visible in 99 % (refer to Figure 6.1 on page 165), they are only used for positioning in 82.5 % of the time travelled. The positioning service unavailability is 17.5 % which is due to a combination of both satellite unavailability and the technical problems mentioned in the previous chapters.

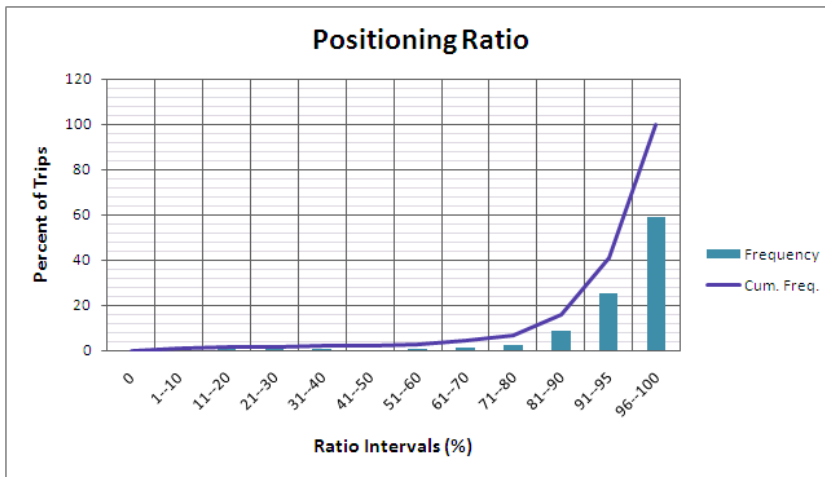
The analyses of satellite availability carried out in London [Ochieng et al., 2003a], showed a satellite availability of approximately 60 % with a geodetic GPS receiver. Compared with these results from 2002, the satellite availability in Copenhagen is nearly 38 % better.

This is again due to the improved receiver technologies and modernization of the GPS system over the years, but also geographical differences between the cities. The density of buildings and urban canyon effect is lower in Copenhagen.

In this research, the following parameter for assessment of the positioning availability has been computed:

**Positioning Ratio** is the ratio of the number of positions logged during a trip to the total duration of the trip expressed as a percentage.

The Positioning Ratio for the 1,000 trips data set is illustrated in Figure 6.10. The ratio demonstrates the correlation between the logged positioning and the total trip duration.



**Figure 6.10:** Positioning Ratio.

The figure illustrates the frequency of different ratio intervals. The results show that for 59 % of the trips the positions logged during a trip constitute between 96–100 % of the total trip duration. From the cumulative frequency the results show that in approximately 16 % of the 1,000 trips, the positioning ratio is less than 90 %. In other words, 84% of the trips have a positioning availability of more than 90 %. The average positioning availability per trip is



92.4 %.

These positioning ratios are important for the design of a GNSS-based continuous charging scheme as they indicate how well each trip have been logged during the experiment. The positioning ratio forms the basis of the usage determination and hence the road charge computation.

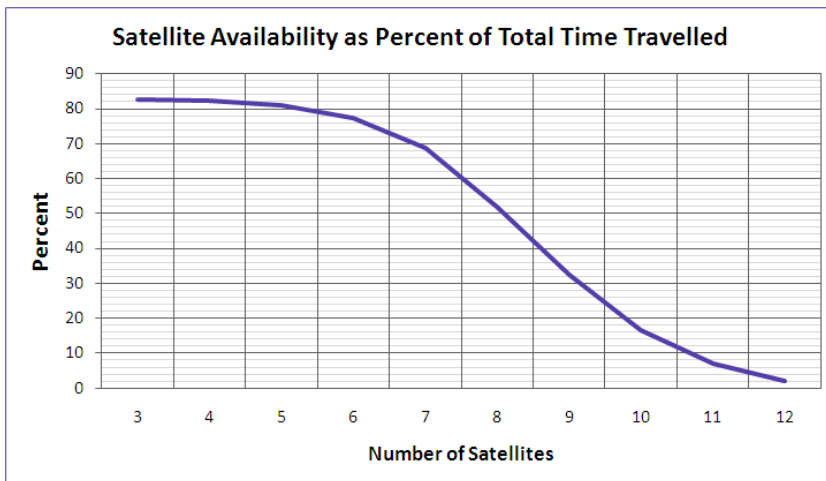
### 6.2.2 Integrity

Integrity is the key liability parameter that relates to the trust that can be placed in the correctness of the information provided by a positioning system [Ochieng and Sauer, 2002]. Determining the level of trust requires redundant measurements. Hence to detect a fault, at least five measurements are required (3D positioning and time determination), and to isolate and exclude a fault, at least six measurements are required.

Considering this basic requirement for integrity for failure detection, the satellite availability figure is 81.1 %. The cumulative frequency of the satellite availability during the total time travelled is given in Figure 6.11. The figure illustrates the availability of redundant measurements from more than four satellites. The availability to isolate and exclude a fault is hence 77.3 %.

Compared to the London experiment in [Ochieng et al., 2003a], for which the availability of at least five satellites for integrity purposes was only 42.5 %, the integrity level in Copenhagen is significantly better.

The integrity results show that the potential of detecting faults based on redundant measurements is possible in approximately 81 % of the total time travelled, which is significantly better than the results from London. This potential enables the possibility of giving timely system warnings when vehicle location determination faults are detected.



**Figure 6.11:** Cumulative Frequency of Satellite Availability during Total Time Travelled.

### 6.2.3 Accuracy

Accuracy describes the closeness of a measured position in relation to the truth. Typically, when assessing the accuracy of kinematic GPS, a high-accuracy receiver is used as a reference for the measurements. In this experiment no reference receiver was available to verify the truth. Alternatively, the positioning accuracy is assessed by comparing the estimated positions with a digital map of the Copenhagen road network, representing the truth (inspired by [Ochieng and Sauer, 2002]). The digital map used as geographical reference for this assessment was provided by Krak. The road centre lines in the digital map are digitized from orthophotos and have an accuracy within seven meters [Krak, 2004]. This margin error should be kept in mind when interpreting the results.

In order to assess the positioning accuracy in relation to the digital map, proximity analyses have been conducted. The proximity analyses reveal the number of GPS positions within a given distance from the centre line of the road.

[Ochieng and Sauer, 2002] defines the following two parameters for

assessment of the positioning accuracy:

**Fix Density** is the ratio of the number of positions meeting a accuracy requirement to the total number of positions expressed as a percentage.

**Total Outage** is the total period of the total time travelled over which the accuracy requirement was not achieved.

Note that this alternative methodology is used as a general estimate of the positioning accuracy, as the methodology does not consider the trip routes. Positions outliers may therefore be classified as meeting the accuracy requirement another place in the map. Table 6.2 summarizes the fix densities and total outage values for the six accuracy bands of 5, 10, 20, 30, 50, 100, 250 and 500 meters.

| Accuracy Level | Fix Density | Total Outage |
|----------------|-------------|--------------|
| 5 m            | 57.95 %     | 51.95 %      |
| 10 m           | 84.04 %     | 30.32 %      |
| 20 m           | 94.73 %     | 21.46 %      |
| 30 m           | 96.63 %     | 19.88 %      |
| 50 m           | 98.11 %     | 18.65 %      |
| 100 m          | 99.85 %     | 17.21 %      |
| 250 m          | 99.96 %     | 17.12 %      |
| 500 m          | 100 %       | 17.09 %      |

**Table 6.2:** Fix Densities within Accuracy Levels.

The results show, the fix densities within accuracy levels as percentage of the total time travelled. For the 5 m level, the fix density is approximately 58 % and for the 100 m level the corresponding figure is 99.85 %. The position fix differences between these two levels are illustrated in Figure 6.12. Furthermore, the results show that the total outage is 51.95 % for 5 m accuracy level (equivalent to 140 hours travel time). For the 100 m accuracy level, the corresponding figure is 17.21 % meaning that nearly 18 % of the total time travelled the GPS positions are more than 100 meters away from the road centre lines. Furthermore the results demonstrate

that while all the logged GPS positions are within 500 m accuracy, the total outage is approximately 17 % due to the positioning unavailability.

Compared to the London results (in [Ochieng and Sauer, 2002]), where the fix density within the 5 m and 20 m accuracy level was 42 % and 99 % respectively, the fix densities in Copenhagen are reasonable. The fix density is higher for the 5 m band, but lower for the 20 m band. It is important to keep in mind that only one route was tested in the London experiment. The total outage values in London, were 83 % and 63 % for the 5 m and 20 m band, which indicates a better performance in Copenhagen as the total outage percentages are significantly lower.

The results for Copenhagen show that the required navigation performance for accuracy is partly met as the computed positions are within 30 meters of the truth in 95 % of the time [Zabic, 2011a]. However, the additional requirement of the computed positions being within 100 meters in 99.9 % of the time is not met, although it is very close. As earlier mentioned, these figures should be interpreted carefully as the trip routes and road dimensions are not considered. This might affect the results to be more positive than in reality while GPS points which are related to small private roads that do not exist in the road network, will fall within a lower accuracy level ( $> 100$  m) and affect the results more negatively.

Figure 6.13 illustrates this example of GPS inaccuracies affecting the results more positively while the map on the same time affects the results more negatively as not all minor roads are represented in the digital road map. This however only concerns a very small percentage of the data set, and since these incorrect effects oppose each other, the results presented should be trustworthy.

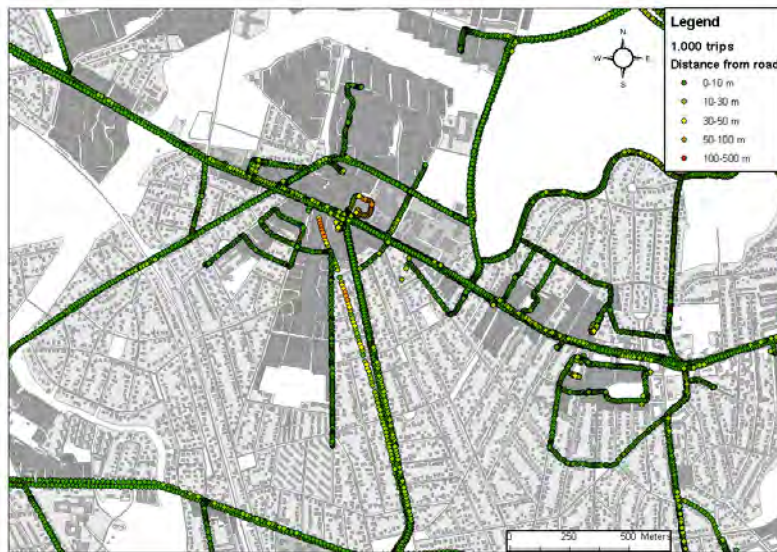
#### 6.2.4 Continuity

Continuity measures the ability of the positioning system to perform its function without interruption, during an intended period of operation. In this section, a methodology for assessing the continuity based on the collected OBU data is developed. To assess



**Figure 6.12:** Fix Densities for 5 m and 100 m Accuracy Levels.





**Figure 6.13:** Proximity Analysis Examples.

the continuity of the positioning function, all interruptions must be identified. As earlier mentioned, it is important to keep in mind that positioning interruptions in integrated OBU equipment may have other causes than positioning unavailability.

For the 1,000 trips, all interruptions (gaps) have been identified and the frequency of gaps per trip is determined and illustrated in Figure 6.14.

The result shows that for 98.5 % of the 1,000 trips, interruptions occurred in the vehicle location determination. For approximately 90 % of the trips, interruptions occurred up to 50 times per trip. In 29 % of these, gaps occurred 1-5 times per trip, and in 18 % and 29 % gaps occurred 6-10 times and 11-25 times respectively. Furthermore, the results show that one trip had more than 500 interruptions. When interpreting these results, it is important to remember that the 1,000 trips data set is selected with a higher level of data validity than in general as all trips have a trip duration, a mileage and an average speed  $> 5$  km/h (refer to Section

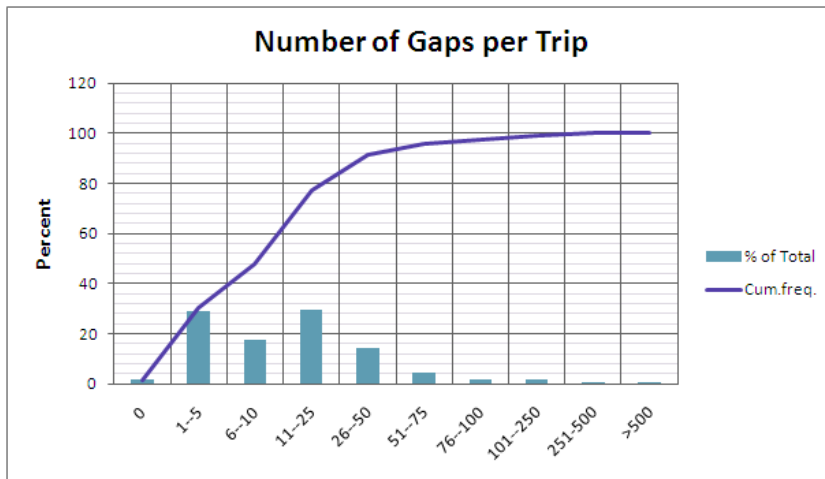


Figure 6.14: Gaps per Trip.

5.5). These 1,000 selected trips should thereby technically represent ordinary trips. The average number of gaps per trip is approximately 22.

#### 6.2.4.1 Gap Duration

The above demonstrated interruptions must be related to the duration of the gaps. The general distribution of gap durations for all trips was illustrated in Figure 5.12 on page 150. The average gap duration for the 1,000 trips is approximately 9 seconds and 3.2 seconds excluding all outliers (gaps above 30 minutes).

For the research presented in this thesis, the following parameter has been computed:

**Gap Duration Ratio** is the ratio of the sum of gap durations in a trip to the total duration of the trip expressed as a percentage.

The Gap Duration Ratio for the 1,000 trips data set is illustrated in Figure 6.15. The ratio demonstrates the correlation between the gap and trip duration. The figure illustrates the frequency of

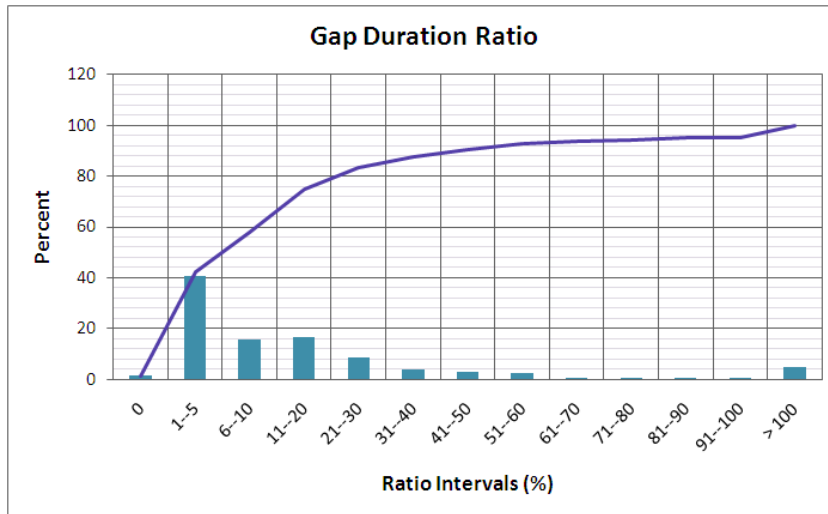


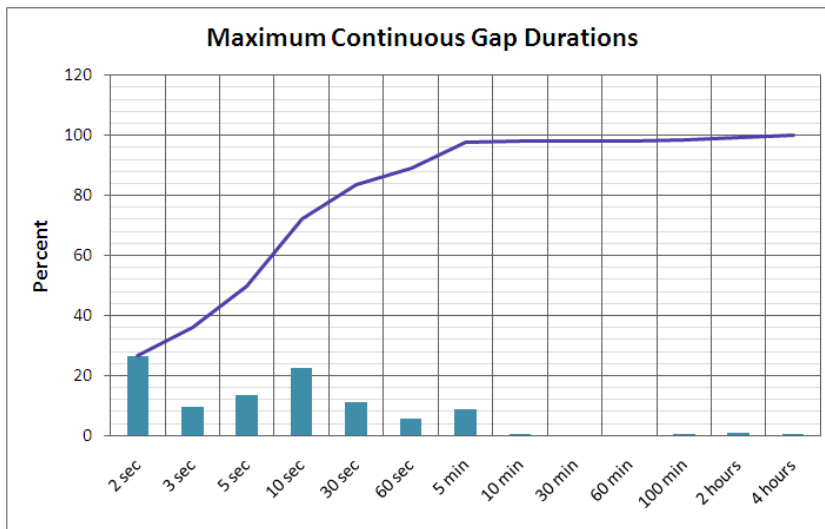
Figure 6.15: Gap Duration Ratio.

different ratio intervals. The results show that the gap durations in 90 % of the 1,000 trips constitute up to 50 % of the trip duration. Around 42 % of these constitute less than 5 %. These figures are important for the charging process as the results show that no vehicle location determination exists in up to a great percentage of the trip durations. The trips with gap duration ratios above 100 % are outliers due to the data invalidity mentioned in the data reliability assessment (section 5.5). The average gap duration ratio for the 1,000 trips excluding these outliers is 13.1 %.

In continuous road charging schemes, the duration of interruptions in the vehicle location determination is important as especially large gaps affect the charge construction. The maximum continuous gap duration is therefore computed per trip.

Figure 6.16 illustrates the distribution of max. continuous gap duration per trip. The results show that approximately 27 % of the 1,000 trips have a max. continuous gap duration of only 2 seconds and that 90 % have a max. continuous gap duration of 60 seconds or less. The figure illustrates that no max. continuous gap durations exist between 10–60 minutes and that 1.7 % of the





**Figure 6.16:** Distribution of Maximum Gap Duration per Trip.

trips have a gap duration of more than 1 hour. Approximately 9 % have a max. continuous gap duration between 1–5 minutes and only 0.4 % have the same between 5–10 minutes. These results indicate that the max. continuous gap duration differs depending on whether it was caused by satellite unavailability or configuration faults in the system setup.

Eliminating these configuration faults (durations  $> 1$  hour), the maximum continuous gap duration for all the 1,000 trips is therefore to be found within the 5–10 minute duration interval and is exactly 562 seconds or 9.37 minutes. In [Ochieng and Sauer, 2002], the maximum continuous outage was found to be 4.7 minutes for a trip driven in central London. The maximum continuous gap duration is an important figure for the design of augmentation systems to support GNSS in the vehicle location determination when the location determination is interrupted.

Figure 6.17 illustrates the spatial distribution of gap durations for the Copenhagen area. The result shows that the majority of gap durations for the Copenhagen area is less than 10 seconds. The gap durations up to one minute are clustered in the densest

parts of Copenhagen. Furthermore the results show that few gap durations of more than 600 seconds (10 min) exist. The large gap durations up to one day are more dispersed in the Copenhagen area, which indicates that these are hence not correlated to the building density.

#### 6.2.4.2 Gap Distance

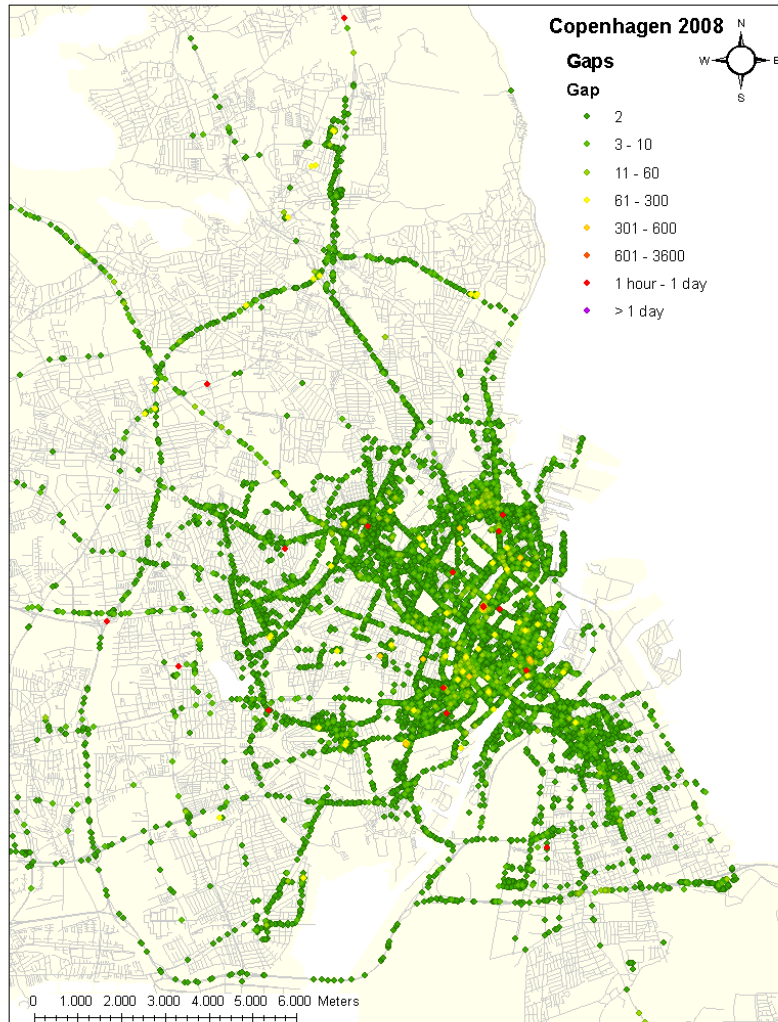
The missing vehicle location determination affects the charging process, as the driven distance during these interruptions can not be determined based on collected data. It is for that reason important to assess the gap distances as these are the distances which the charge construction function have to estimate in order to determine the distance driven. The gap distance is proportional to the vehicle's speed in the gap moment. The distribution of gap distances within different distance intervals are given in Figure 6.18.

The figure illustrates that approximately 65 % of the gaps in the 1,000 trips are less than 10 meters. Nearly 18 % of those have a zero gap distance. In addition, the figure shows that very large gap distances exist in the data, but these constitute only 0.3 % in total. 99 % of the gap distances are within 200 meters. The average gap distance including all outliers is 899 meters and 15 meters for gap distances less than 5 kilometers.

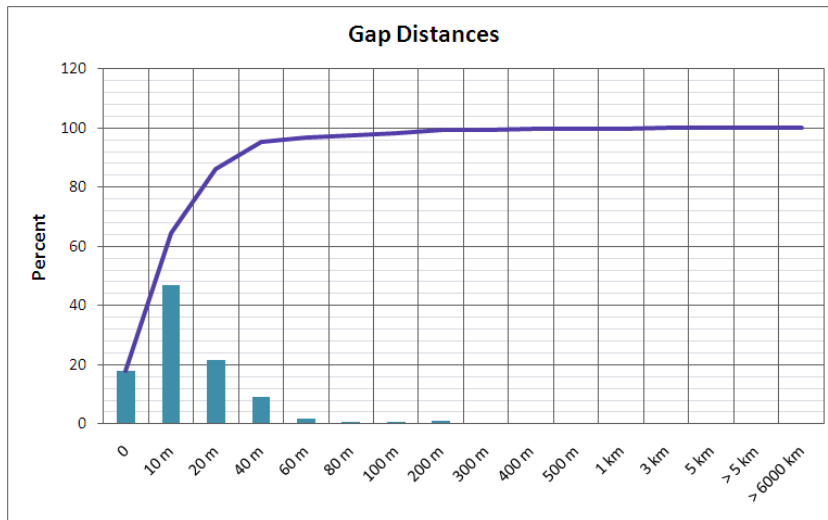
For the research presented in this thesis, the following parameter has been computed:

**Gap Distance Ratio** is the ratio of the sum of gap distances in a trip to the total distance of the trip expressed as a percentage.

The Gap Distance Ratio for the 1,000 trips data set is illustrated in Figure 6.19. The ratio demonstrates the correlation between the gap and trip distance. The figure illustrates the frequency of different ratio intervals. The results show that in approximately 53 % of the trips, the gap distance constitutes between 1-5 % of the trip mileage. In addition, the cumulative frequency demon-



**Figure 6.17:** Spatial Distribution of Gap Durations.



**Figure 6.18:** Distribution of Gap Distances.

strates that the gap distance for approximately 90 % of the trips constitutes less than 30 % of the trip mileage. It is important to keep in mind that the trip distances are based on the OBUs trip mileage measurements. The average gap distance ratio excluding outliers ( $> 100$  %) is 10.7 %.

With these gap distances, there is a lack in the determination of driven distance which forms the basis for usage determination and charge computation. It is therefore important to determine the maximum continuous gap distances per trip to identify the distances for which alternative distance determination must be provided. The maximum continuous gap distance is therefore computed (as the crow flies) per trip. The frequency of different maximum continuous distance intervals are given in Figure 6.20.

The results show that the maximum gap distance in the majority of the trips is between 20–40 meters. In addition, the cumulative frequency demonstrates that the maximum distance for approximately 80 % of the trips is less than 80 meters and 90 % is less than 200 meters. In other words, approximately 10 % of the trips have a maximum continuous gap distance of more than 200 meters.

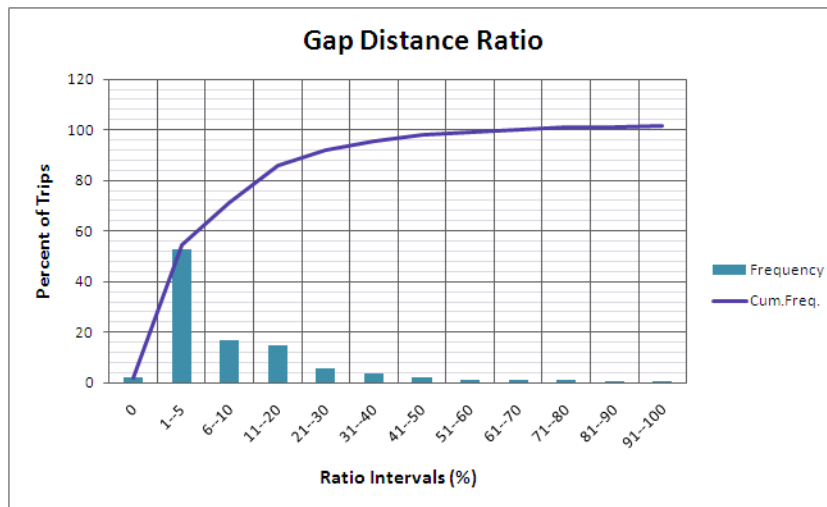


Figure 6.19: Gap Distance Ratio.

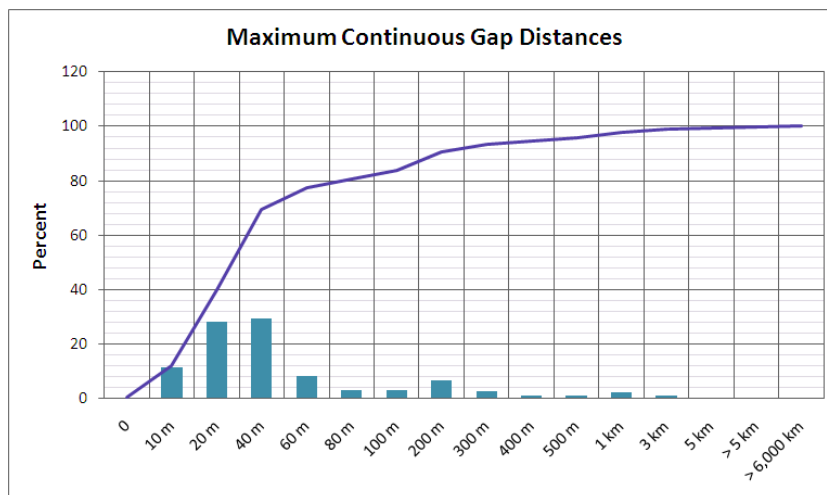


Figure 6.20: Distribution of Maximum Continuous Gap Distances.

Furthermore, the figure shows that large maximum continuous distances exist in the 1,000 trips data set. Gap distances of more than 6,000 kilometers are very rare in the data set (0.3 %) and are hence considered as outliers in the data set. The maximum continuous gap distance for all the 1,000 trips is found to be 6.63 kilometers.

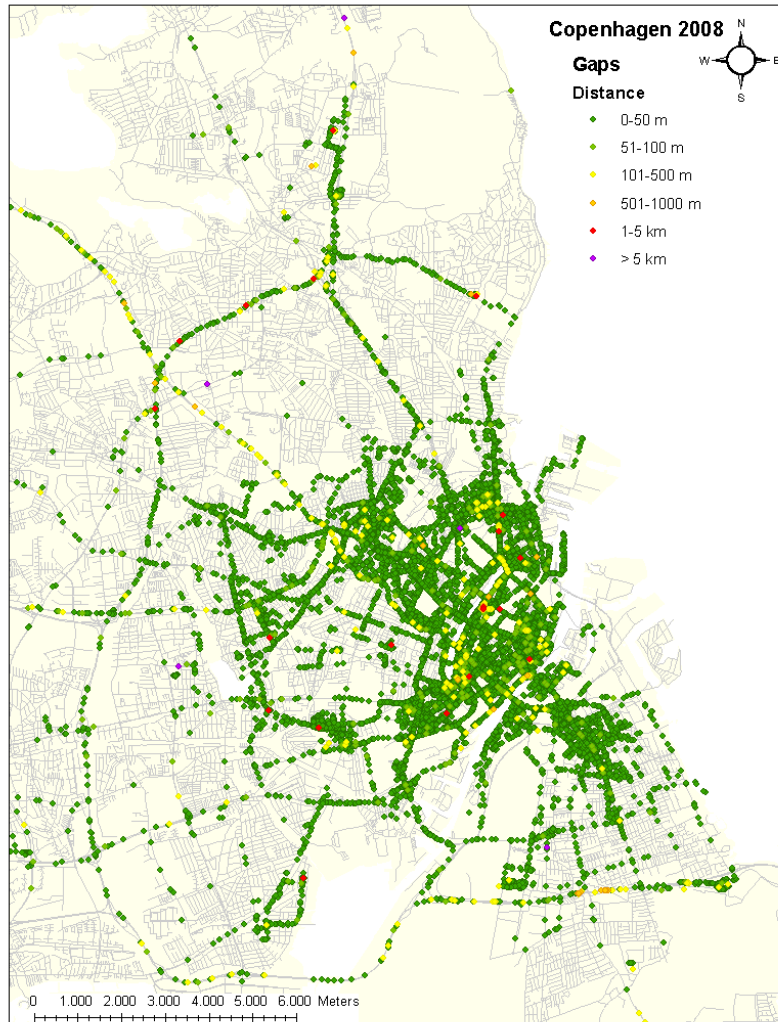
Figure 6.21 illustrates the spatial distribution of gap distances for the 1,000 trips data set. The result shows that the majority of gap distances for the Copenhagen area is less than 50 meters. The gap distances up to 1,000 meters are partly clustered in the densest parts of Copenhagen and on the main roads due to the higher speed. These gap distances are also found in connection with tunnels and bridges in the Copenhagen area. Furthermore the results show that few gap distances of more than 5 kilometers exist in the data set.

The gap distance results are important for the design of the charge construction function as the gap distances missing in the total trip distances need to be estimated in order to charge the road users correctly for their road usage.

### 6.2.5 Discussion on Navigation Performance

In this section, the GNSS navigation performance has been assessed based on the required navigation performance parameters - availability, accuracy, integrity and continuity.

The results of the positioning availability assessment showed that the availability of the minimum required four satellites during the total time travelled was approximately 82.5% in Copenhagen. The positioning service unavailability was hence found to be 17.5 %. Compared to similar results from London in 2002, the positioning availability is nearly 38 % better in Copenhagen. From the positioning ratio, the results showed that approximately 84% of the trips had a positioning availability of more than 90 %. The average positioning availability per trip is 92.4 %. These positioning ratios are important for the design of a GNSS-based continuous charging scheme as they indicate how well each trip have been logged during the experiment.



**Figure 6.21:** Spatial Distribution of Gap Distances.

Considering this basic requirement for integrity for failure detection, the satellite availability figure was found to be approximately 81 %. This means that the navigation function's ability to provide warnings, when the navigation system can not be used for correct positioning, was possible in 81 % of the total time travelled. The need for providing warnings depends on the road charging system design and may vary from scheme to scheme. Compared to the integrity results from London in 2002, the results are significantly better for Copenhagen in 2008.

The results of the accuracy assessment showed that the position fix density for the 30 m accuracy level is 96.63 %. This means that approximately 97 % of the position measurements were within 30 m from the road center line, which meets the RNP requirements for liability-critical road transport applications. Furthermore, the results show that the total outage is 19.88 % for the 30 m accuracy level, meaning that in almost 20 % of the total time travelled the GPS positions were more than 30 meters away from the road centre lines. The fix density and total outage for the 100 m accuracy level was 99.85 % and 17.21 % respectively. These results indicate that if a GNSS-based road charging system based on payment zones is implemented in Copenhagen, buffer zones of 100 meters on average would be necessary to ensure that the position measurements are within the correct zone in 99 % of the cases. Compared to the results from the TfL Trials in London [Evans et al., 2005] in section 4.5.1, the corresponding figure was 60 meters on average. However, when interpreting the results from the accuracy assessment presented, it is important to keep in mind that a digital map is representing the truth. In addition, the methodology does not consider road widths or the route driven. However compared to similar results from the London experiment in 2002 [Ochieng and Sauer, 2002], the results from Copenhagen are significantly better.

The continuity results from this assessment showed that in 98.5 % of the 1,000 trips, interruptions occurred in the vehicle location determination. For approximately 90 % of the trips, interruptions occurred up to 50 times per trip. When interpreting these results, it is important to remember that the 1,000 trips data set is selected



with a higher level of data validity than in general as all trips have a trip duration, a mileage and an average speed  $> 5$  km/h. The average number of gaps per trip was found to be approximately 22. The continuity results furthermore showed that the maximum gap duration in 27 % of the 1,000 trips was only two seconds. The maximum duration for approximately 90 % of the gaps was less than 60 seconds. In other words, approximately 10 % of the trips have a maximum continuous gap duration of more than 60 seconds. The results indicated that the maximum continuous gap durations depend on whether it is due to satellite unavailability or system configuration faults. The maximum continuous gap durations due to satellite unavailability for all the 1,000 trips were found to be within the 5–10 minute duration interval. The average gap duration for the 1,000 trips was approximately 9 seconds and 3.2 seconds excluding all outliers (gaps above 30 minutes).

The Gap Duration Ratio results showed that the gap durations in 90 % of the 1,000 trips constitute up to 50 % of the trip duration. The gap duration figures are important for the charging process as the results show that no vehicle location determination exists in up to 50 % of the trip durations. However, 42 % of these constitute less than 5 % of the trip durations. The average gap duration ratio excluding outliers is 13.1 %. These figures are important for GNSS-based road charging systems as the missing vehicle location determination affects the charging process, since the driven distance during these interruptions can not be determined based on collected data.

The gap distance results showed that the gap distances in the majority of the trips (65 %) was less than 10 meters. The gap distance results are important as these are the distances which the charge construction function has to estimate in order to determine the distance driven. The results showed that the maximum gap distance in the majority of trips were between 20–40 meters. In addition, the cumulative frequency demonstrated that the maximum distance for approximately 90 % was less than 200 meters. The maximum continuous gap distance for all the 1,000 trips was found to be 6.63 kilometers. In addition, results showed that the

gap distance for approximately 90 % of the trips constituted less than 20 % of the trip mileage. The gap distance results are important for the design of the charge construction function as the gap distances missing in the total trip distances need to be estimated in order to charge the road users correctly for their road usage.

Summarized, these figures from the RNP assessment demonstrated that the performance of the four required navigation parameters differs significantly. Even though the satellite visibility was shown to be available in Copenhagen, the positioning availability in this experiment was restricted to 83 % of the total time travelled and did not meet the performance requirement of 99 % availability. The high level of positioning unavailability was in this experiment mainly due to inadequate positioning continuity, which was demonstrated by both minor gaps ( $< 10$  minutes) and also very large gap durations. The large gap durations were considered as outliers due to the technical problems during the experiment. However, the positioning accuracy results were good for Copenhagen and partly meet the RNP requirements with approximately 97 % position fixes within 30 meters from the road centerline. The figures presented should be kept in mind when designing GNSS-based road charging systems as different technical failures may happen, which will have severe consequences if not detected in time. The positioning integrity will be able to support failure detection of the vehicle location determination function in 81 % of the time.

### 6.3 Time To First Fix

The availability of positioning measurements is furthermore affected by Time To First Fix (TTFF). TTFF is a specification that details the required time for a GNSS receiver to acquire signals and navigation information (almanac and ephemeris data) from satellites and the time to calculate a solution for the first position fix (refer to section 4.3.2). The receiver acquisition time and hence TTFF can vary depending on the GPS receiver model and a variety of other factors. The almanac contains satellite orbit

information and allows the GPS receiver to predict which satellites overhead, hence shortening the acquisition time [Misra and Enge, 2006]. However, the receiver must have a continuous fix for approximately 15 minutes to receive a complete almanac from the satellites. The ephemeris data contains precision corrections to the almanac data and is required for accurate positioning [Kaplan and Hegarty, 2006]. The ephemeris data is continuously updated and so within a deactivated receiver the ephemeris data will become obsolete after 3-6 hours. In general, the acquisition times given by receiver manufacturers are based on isolated test conditions and do not take influencing factors such as satellite geometry or urban canyon effect into consideration. In typical outdoor conditions, it might take about a minute for a unit to find its starting location depending on when the receiver was last used. In the following the three most common acquisition scenarios are described:

If the receiver was used the last time within two hours (**hot start**), the almanac and ephemeris data kept in the receiver memory is still valid and the receiver only needs the timing information from the satellites to calculate a position. The TTFF for a hot start is typically between 0–25 seconds. If the receiver last was used after more than two hours (**warm start**), the receiver can predict which satellites are overhead but needs to update current ephemeris data before it can calculate the first position. The TTFF for a warm start is typically 25–45 seconds. However, if the receiver has not been used for more than three days, reset or turned off in a location with limited satellite visibility (**cold start**), the GPS receiver cannot predict the satellites overhead and needs to work through an internal list of all satellites, trying to acquire each one in turn. The TTFF for a cold start is anywhere between 2–30 minutes.

As TTFFs in worst cases may be up to  $\frac{1}{2}$  15-30 minutes, they can have a severe impact on the determination of distance driven in continuous road charging schemes. In the literature, TTFF are considered the main problem in relation to GNSS-based road charging systems [Zijderhand et al., 2006].

Often, TTFFs are analysed for different GNSS receiver types and compared to identify the duration of hot, warm and cold starts.

[Sheridan, 2009] provides a summary of different GNSS receivers used in OBUs. These analyses are often based on static measurements or on special equipment, hence the methodologies cannot be directly applied to TTFF analyses based on OBU data from a road charging experiment. In this section, a methodology for assessing the TTFF based on the collected data are presented. To the author's knowledge, TTFF assessments have been difficult to perform in GNSS-based road charging experiments as the vendor equipment was not designed to isolate and identify the TTFF gaps [MapFlow, 2007] and furthermore had start-up delays [Zijderhand et al., 2006].

Based on gap data set, developed for this research, the TTFF is assessed on the basis of TTFF gap durations, distances and spatial distributions. The results are compared to relevant research on the TTFF performance (refer to the literature study in Chapter 4). The analyses and results are presented in the following sections.

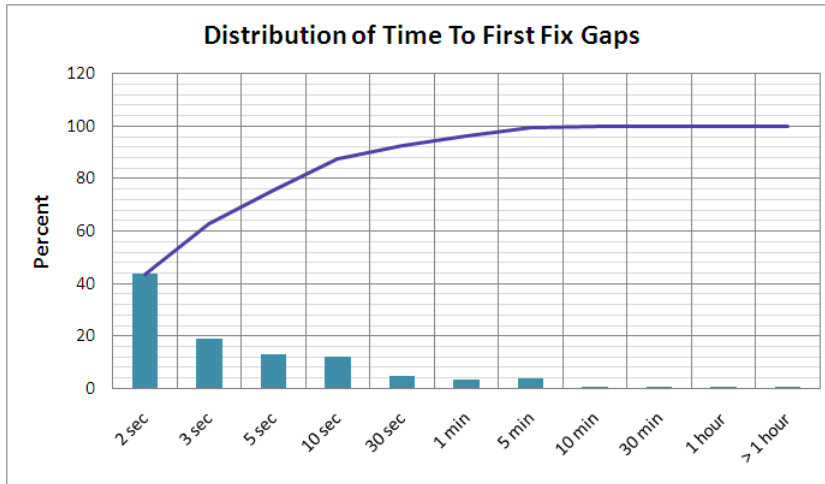
### 6.3.1 Time To First Fix Gap Durations

As the OBUs in this experiment were designed to store the last position measurement from the previous trip as first record in a new trip, the TTFFs could be determined in this research. The TTFF is determined as the duration from the ignition is on to the first position measurement in a trip.

This section analyzes the TTFF gaps, which in this thesis is defined as the gap duration to the first position measurement in trips where TTFF is not instantaneous (i.e.  $TTFF > 1$  sec). The frequency of TTFF gaps within different duration intervals is given in Figure 6.22.

The results show that 99 % of TTFF gaps are less than 160 seconds. The figure demonstrates that very large TTFFs of more than one day exist but these are very rare in the data set. TTFF gaps of more than 30 minutes constitute 0.12 %. Approximately 43 % of the TTFF gaps have a duration of only two seconds. Furthermore, the results from this analysis show that 38.7 % of all trips have a TTFF gap which in total constitute 2.8 % of the total time

travelled. Hence, in approximately 61 % of all trips the GPS receiver logged the first position measurement instantaneously. The TTFF gaps constitute 6 % of the total number of gaps and also 6 % of the total gap duration.



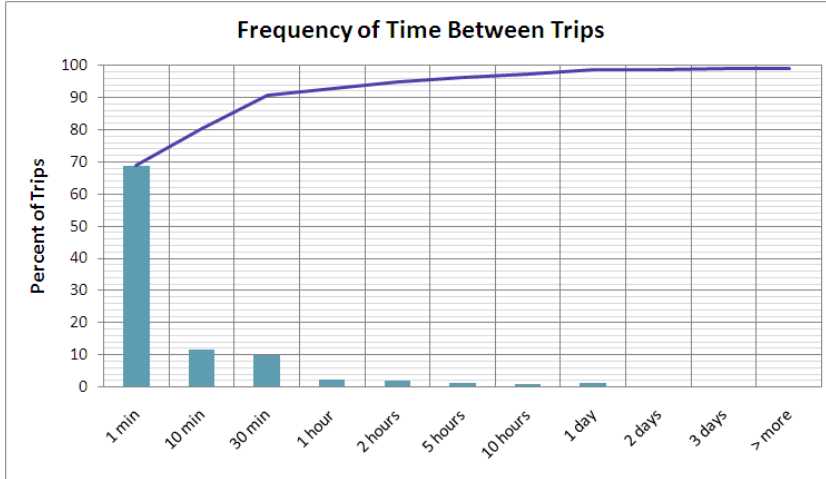
**Figure 6.22:** Time To First Fix.

The average duration of the TTFF gaps including all trips and outliers is approximately 34 seconds. For TTFF gaps less than 30 minutes, the average TTFF is 11 seconds. Compared to [Zijderhand et al., 2006], in which the average TTFF in The Netherlands was estimated to be 130 sec +/- 13 sec, the results from Copenhagen presented in this section are significantly lower. The TTFF gap durations inclusive outliers constitute approximately 2.8 % of the total time travelled.

In relation to the three acquisition time scenarios presented, this section therefore assesses TTFF gaps compared to the time duration between the trips.

Figure 6.23 illustrates the distribution of time between trips (TBT) in the data set. The figure shows that in approximately 69 % of the trips, the TBT is less than 1 minute, which is due to technical problems regarding on/off switching OBUs during the experiment (refer to Chapter 5). Several trips have a TBT between 10–30

minutes due to the selection of participants which include taxis and parking attendant vehicles that conduct many short stops during the day.



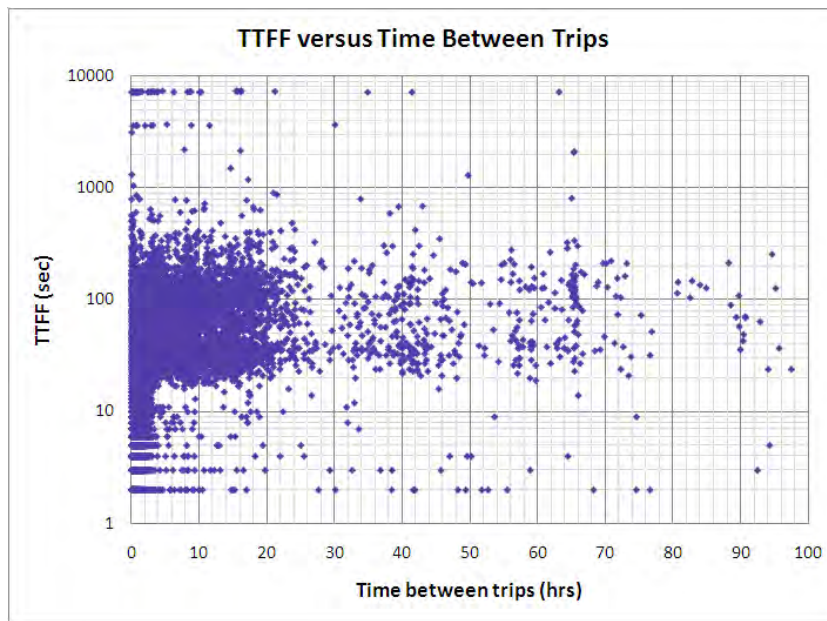
**Figure 6.23:** Distribution of Time Between Trips.

In Figure 6.24, the TTFF gap duration is compared to TBT. The figure illustrates that no clear correlation between TTFF and TBT exists. One would expect a reasonable linear correlation between time-to-first-fix and the time between trips. However, [Zijderhand et al., 2006] concludes that there is no correlation between the time between trips and TTFF.

In order to assess this correlation further, the trips were divided into three subsets according to their startup situation based on the TBT. These three subsets are:

- Hot starts:  $TBT \leq 2$  hours
- Warm starts:  $TBT > 2$  hours and  $\leq 3$  days
- Cold starts:  $TBT > 3$  days

Figure 6.25 illustrates the distribution of TTFF gaps within the three subsets. The figure demonstrates that the distribution of TTFF gaps differs between the three categories. The TTFF gap durations for hot starts are significantly shorter than for warm

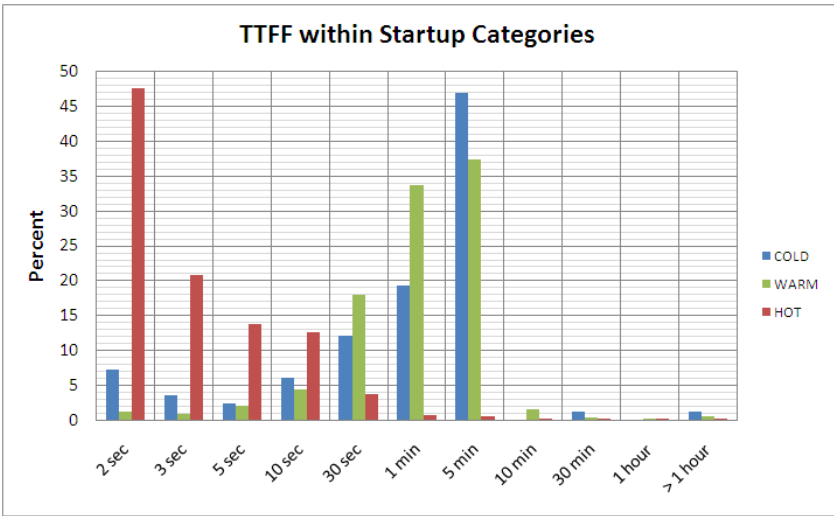


**Figure 6.24:** Time To First Fix compared to Time Between Trips.

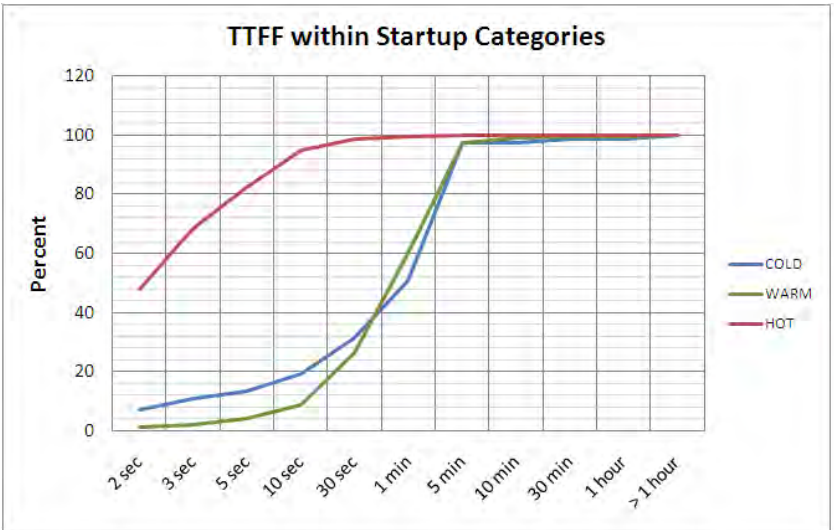
and cold starts. For warm and cold starts, the TTFF gap duration distributions are very similar, which presumably is due to the rather unclear definition of warm and cold starts. In Figure 6.26 the cumulative frequency of TTFF gaps within the three subsets is given. The figure shows that approximately 99 % of the TTFF gaps for hot starts are less than 30 seconds, while 99 % of the TTFF gaps for warm and cold starts are within 5 and 10 minutes respectively.

Table 6.3 shows the distribution of trips between TTFF gap intervals and the startup categories. The results show that the OBUs in 32.7 % of all trips had hot starts within 2–8 seconds. In addition, 1.3 % of all trips had warm starts between 9–40 seconds and 0.08 % trips had cold starts with TTFF gap durations of more than 100 seconds.

The spatial distribution of TTFF gaps is furthermore analysed in this thesis and the result is illustrated in Figure 6.32 on page 208.



**Figure 6.25:** Distribution of TTFF Gap Durations within Startup Categories.



**Figure 6.26:** Cumulative Frequency of TTFF Gaps within Startup Categories.



| TTFF       | 2–8 sec | 9–40 sec | 41–100 sec | >100 sec |
|------------|---------|----------|------------|----------|
| Hot Start  | 32.74 % | 2.41 %   | 0.21 %     | 0.14 %   |
| Warm Start | 0.22 %  | 1.33 %   | 0.86 %     | 0.76 %   |
| Cold Start | 0.011%  | 0.011 %  | 0.014 %    | 0.076 %  |

**Table 6.3:** Time To First Fix Scenarios.

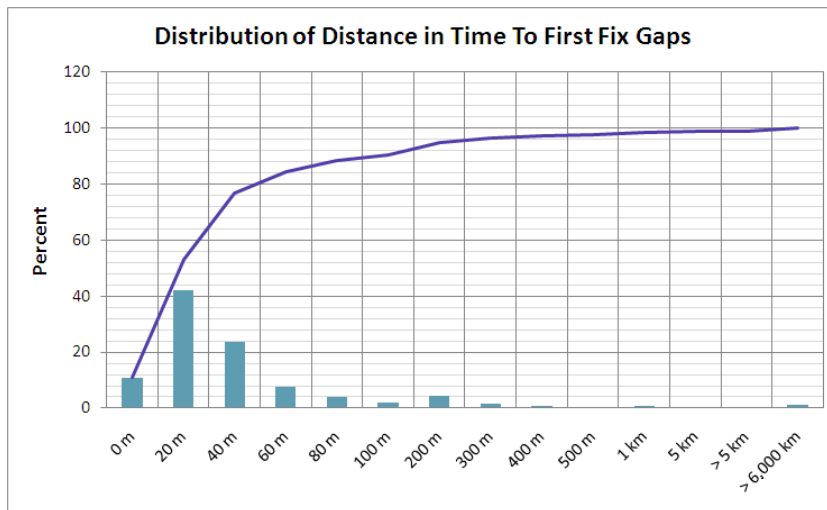
The figure illustrates the position in which the vehicle ignition is turned on for all the 1,000 trips. Note that the spatial distribution is layered with the largest durations on top. The result shows that the small TTFF gaps have occurred in most of the Copenhagen area. The large TTFF gaps ( $> 60$  sec) are clustered in the densest parts of Copenhagen and hence affected by urban canyons. The outliers ( $> 1,800$  sec) are more dispersed which confirms that these very large TTFFs are outliers caused by technical problems rather than cold starts.

### 6.3.2 Time To First Fix Gap Distances

TTFF gaps result in missing distance information. This distance information is important in relation to the road charging process as it may influence the determination of the distance driven in continuous charging schemes. This section analyzes the DTFF gaps, which in this thesis is defined as the gap distance to the first position measurement in trips where TTFF is not instantaneous (i.e.  $\text{TTFF} > 1$  sec).

The DTFF is determined as the gap distance from the end position measurement in the previous trip to the first position measurement in a new trip. The gap distances between these two position measurements were calculated by the Haversine Formula [Sinnott, 1984] for distance determination between two points in spherical coordinates (refer to Appendix A for explanation). The frequency of TTFF gap distances within different intervals is given in Figure 6.27.

The results show that the DTFF varies from zero to very large distances of more than 6,000 km. The distances above 6,000 km



**Figure 6.27:** Distribution of Distance To First Fix.

occur in 1.2 % of the total number of TTFF gaps and are due to the GPS receiver logging the first position measurement as in the center of Earth (Origo 0,0,0). These DTFFs are hence related to the radius of the Earth.

Furthermore, the results show that approximately 90 % of the DTFFs are less than 100 meters and 22 % are less than 10 meters. The average DTFF is approximately 77 meters.

Figure 6.28 illustrates the DTFF compared to the TTFF gaps. The result shows that the distances to first fix vary a great deal in relation to the time to first fix, although a small increase in the DTFF can be seen proportional to the TTFF gap durations.

This correlation is more evident in Figure 6.29 which illustrates the distribution of DTFF within the three different startup categories. The results show that the DTFFs are significantly shorter for hot starts than for trips with warm or cold starts. As with the TTFF, the difference between warm and cold starts is not very significant, although the figure clearly illustrates that the majority of DTFFs of more than 6,000 kilometers are related to trips with cold starts.

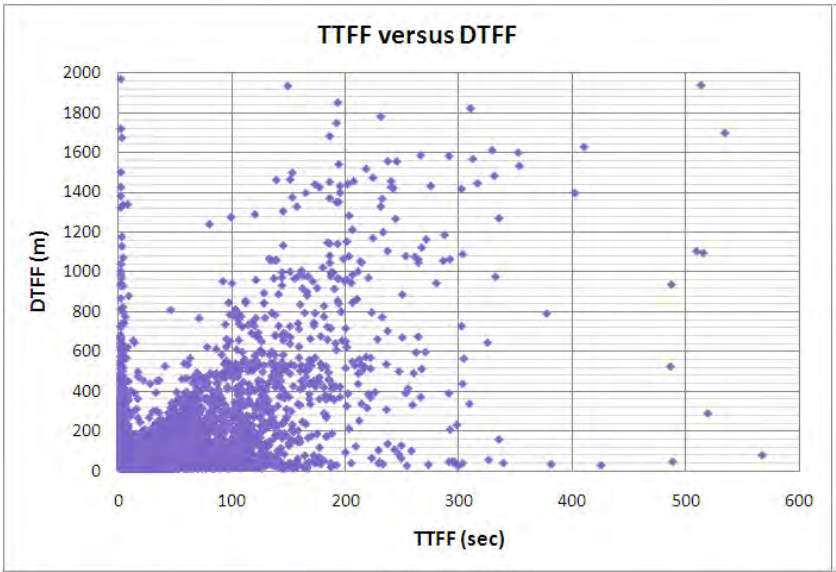


Figure 6.28: Time To First Fix Compared to Distance to First Fix.

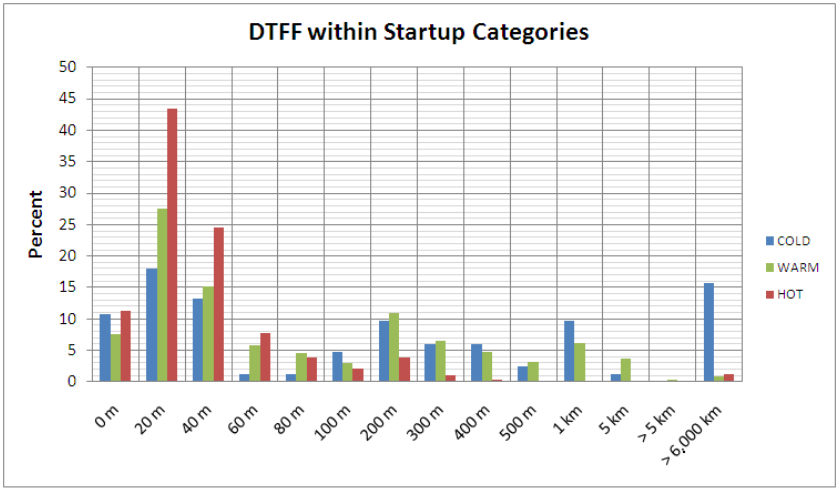
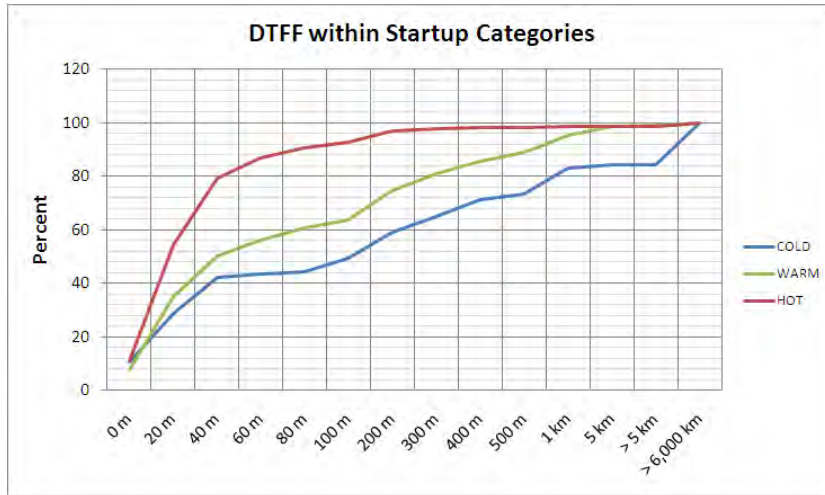


Figure 6.29: Distribution of Distance To First Fix within Different Startup Categories.

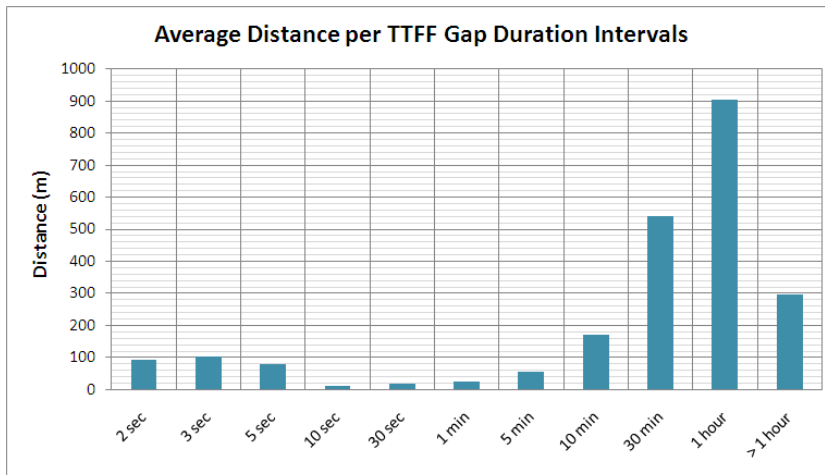
In Figure 6.30 the cumulative frequency of DTFF gaps within the three categories is given. The figure shows that approximately 90 % of the DTFF gaps for hot starts are less than 80 meters, while only 60 % and 45 % of the DTFF gaps are less than 80 meters for warm and cold starts respectively.



**Figure 6.30:** Cumulative Frequency of Distance To First Fix within different Startup Categories.

The average DTFF within different TTFF gap duration intervals for all trips including outliers is summarized in Figure 6.31.

The spatial distribution of the TTFF gap distances is furthermore analysed in this thesis and the result is illustrated in Figure 6.33 on page 209. The figure illustrates the starting point for the gap distances of all 1,000 trips, layered with the largest distances on top. The result shows that the distance of the majority of TTFF gaps in Copenhagen is less than 10 meters. The small gap distances (< 10 m) are dispersed in the Copenhagen area. The larger gap distances are clustered in the densest parts of Copenhagen, while the largest gap distances of more than 1 kilometer are more dispersed. Some of the gap distances above 6,000 kilometers are found at the DTU Transport Campus Ares, which indicates that these large gap distances might be due to restarting of the OBUs



**Figure 6.31:** Average Gap Distances for Time To First Fix Durations.

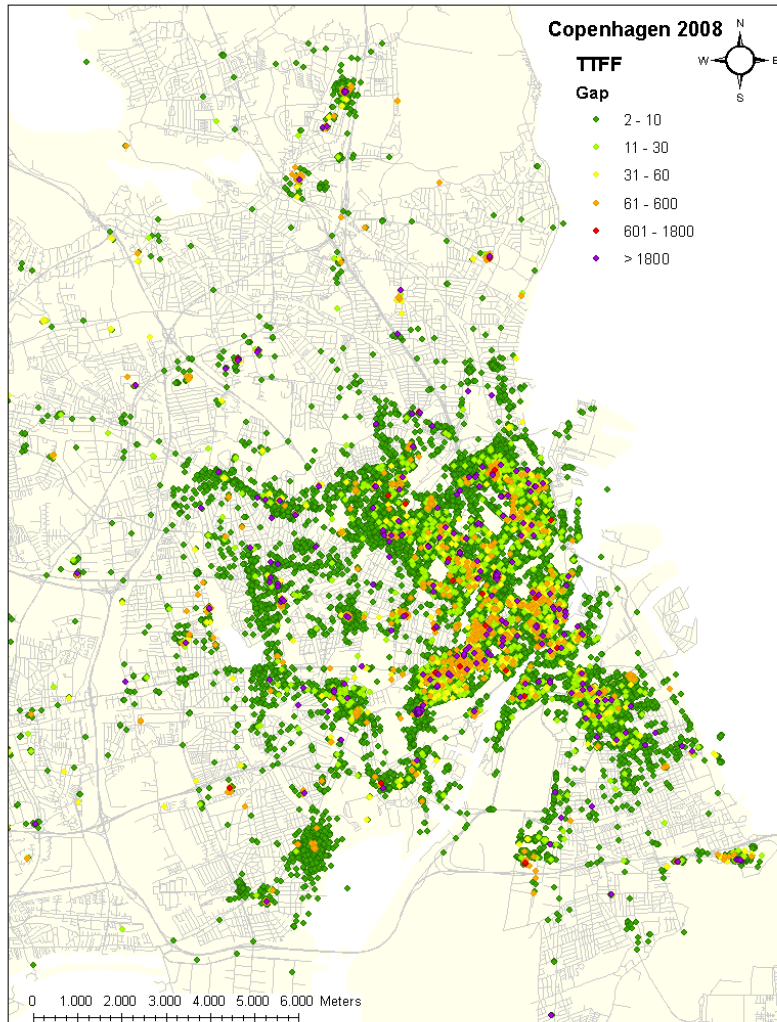
for different technical reasons.

### 6.3.3 Discussions on TTFF

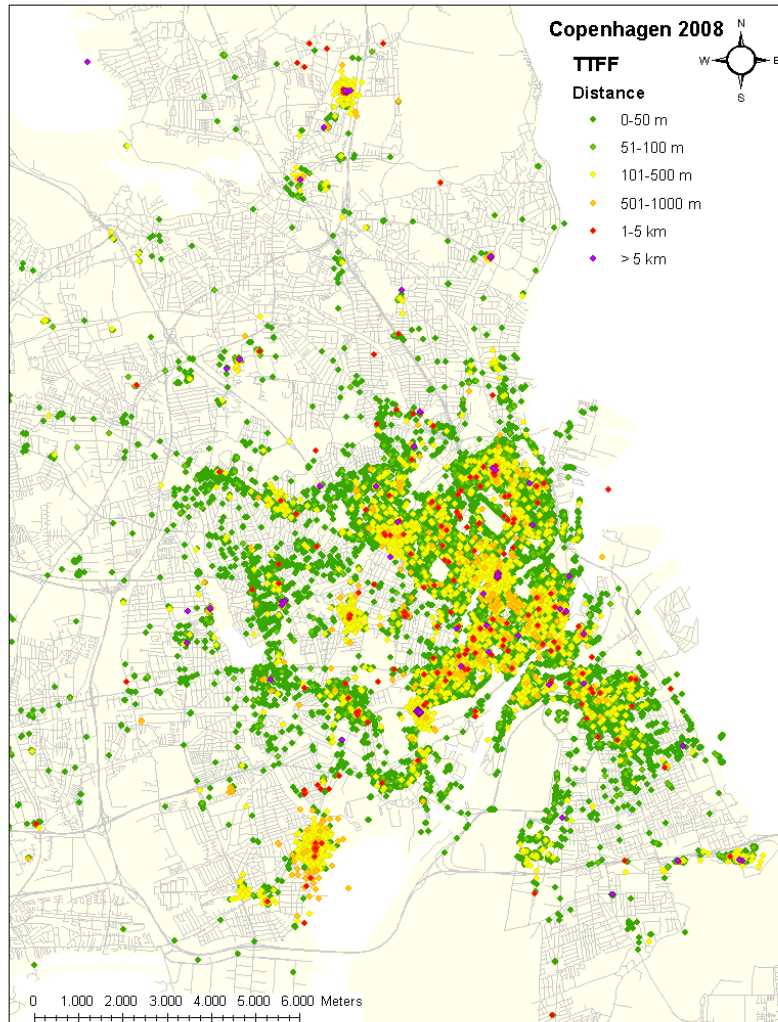
The Time To First Fix has been analyzed in this section based on gap durations and gap distances. The TTFF is an important measure to assess and understand in relation to GNSS-based road charging systems as the availability of positioning measurements is affected.

The results of this assessment showed that approximately 39 % of all trips had a TTFF gap before the first position measurement in a trip. 99 % of these TTFF gaps were less than 160 seconds and in total all TTFF gaps constituted 6 % of the total number of gaps during the experiment and 2.8 % of the total time travelled. The average TTFF gap duration was 11 seconds excluding all outliers. In 61 % of the trips the OBU logged the first position measurement instantaneously.

In addition, the results of the analyses showed that the TTFFs in approximately 99 % of the trips with hot starts were within 10



**Figure 6.32:** Spatial Distribution of Time To First Fix.



**Figure 6.33:** Spatial Distribution of Time To First Fix Distances.

seconds, meaning that the GPS receivers kept up-to-date almanac and ephemeris information in the receiver memory and only needed to obtain timing information from the satellites to calculate a position fix.

Furthermore, the results showed that 90 % of the TTFF gap distances were less than 100 meters and 22 % were less than 10 meters. The average TTFF gap distance was found to be approximately 77 meters. This TTFF assessment furthermore demonstrated a correlation between the time- and distance to first fix, which showed that 90 % of the DTFF for hot starts are less than 80 meters while only 60 % and 45 % are within the same distance for warm and cold starts respectively.

This section has presented a methodology for assessing the TTFF based on the collected data from OBUs. This methodology does not consider the data integrity in terms of data invalidity and deficiency. The very large TTFF gap durations (outliers) may therefore be a consequence of the technical problems which occurred during the experiment (refer to Section 5.5). The results however demonstrate that TTFF gaps constitute an important part of both the total number of gaps and the total time travelled.

## 6.4 Discussions on Vehicle Location Determination Performance

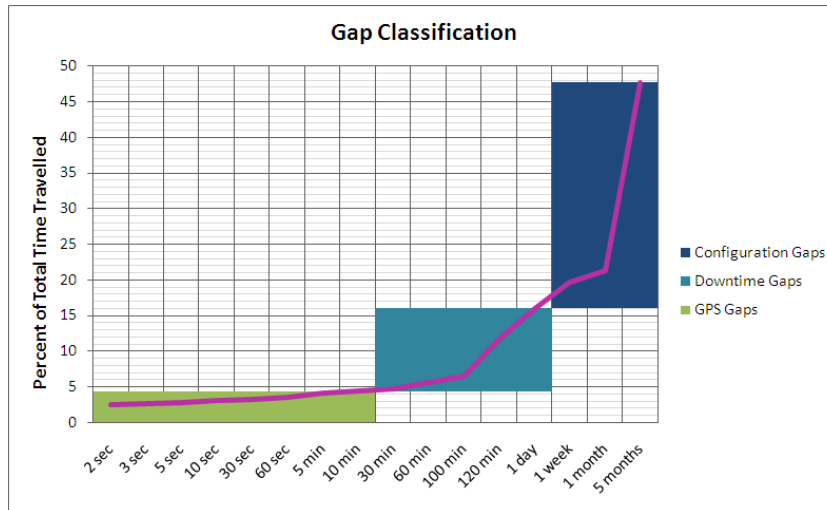
The assessment of the vehicle location determination performance in this chapter has showed a high level of unavailability. A large percentage of the unavailability was due to the technical problems resulting in system downtime gaps and gaps caused by incorrect system configuration. Based on the results from the assessments presented in this thesis, the positioning gaps are in this thesis classified into three overall categories:

**GPS gaps** which are the minor gaps less than ten minutes primarily caused by GNSS unavailability including time to first fix gaps.



**Downtime gaps** which are the gaps with durations less than a day. These gaps are primarily caused by technical problems or system maintenance resulting in positioning downtime.

**Configuration gaps** are large gaps with durations lasting more than a day. The large gaps are primarily caused by technical configuration faults in the system set-up, resulting in incorrect gap durations or long periods of positioning downtime.

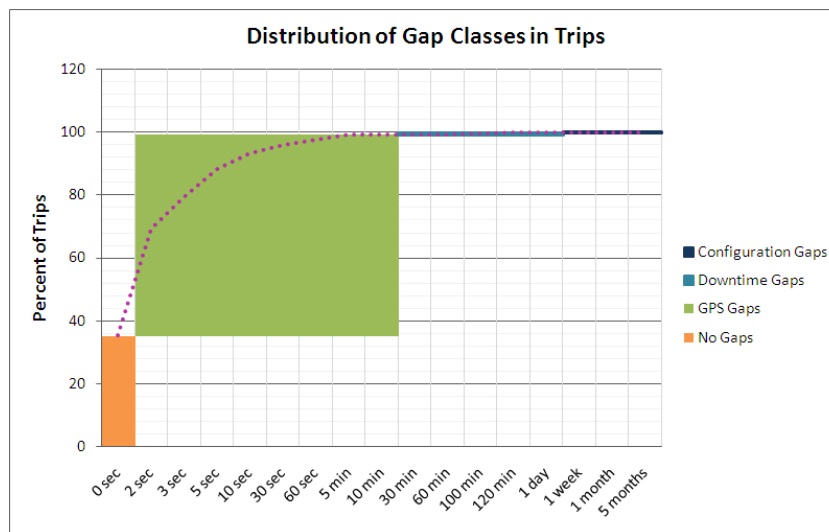


**Figure 6.34:** Gap Classification in Percent of Total Time Travelled.

These gap categories and their contribution to the unavailability of the vehicle location determination function are illustrated in Figure 6.34.

The figure illustrates that if the gaps due to configuration faults are eliminated the positioning unavailability drops from 47 % to 16 % of the total time travelled. And if, in addition, the downtime gaps can be eliminated, the unavailability drops to 4.7 %. Although both the configuration faults and downtime gaps may be decreased significantly, it is unrealistic to believe that these will be completely eliminated in future setups as both faults and failures occur in every system. In addition, mandatory system down time will be necessary from time to time in order to maintain, update

or repair the road charging system. What the figure furthermore demonstrates is that the GPS gaps constitute the smallest part of the positioning unavailability, although 4.7 % does not meet the availability requirement of liability-critical road charging systems. Although the large gaps caused by system downtime and configuration faults constituted a large percentage of the VLD unavailability, these gaps only constituted a small percentage in the total number of gaps (refer to Figure 6.35). Figure 6.35 illustrates the distribution of the gap classes within the percentage of trips. The results demonstrate that while approximately 37 % of trips have zero gaps in their positioning, nearly 62 % of trips have GPS gaps in the position measurements. The large gaps caused by system downtime and configuration faults only occur in about 1 % of the trips. In addition, the majority of gaps was found to be less than 25 seconds and in most trips the total duration of the gaps was between 2–5 seconds. These results hence indicate that the main concerns regarding the unavailability of the vehicle location determination should be how to eliminate the large downtime and configuration and reduce the occurrence of the many GPS gaps.



**Figure 6.35:** Distribution of Gap Classes within the Percentage of Trips.

According to the road charging system's spatial degree of detail, different requirements are specified on the vehicle location determination performance. Table 6.4 summarizes the VLD performance assessment from this chapter in relation to the most common GNSS-based charging schemes. The table demonstrates that if the system is based on charging zones, where the road users pay different tariffs per kilometre within different zones, the performance of the VLD function is quite good. The accuracy performance is sufficient for determining which zone the vehicles are within (including buffers) and the level of continuity is fair for determining the driven distance. If the road charging scheme is based on individual road segments or on road types, the performance level is moderate for determining the accurate routes on which the cars are driven. For charging schemes based on discrete events (passing a cordon or a specified point), the VLD performance level is slightly lower as charging schemes based on discrete event set higher requirements to positioning availability when passing the charging event. However, the use of different algorithms can help detect whether the vehicles have passed a specific event.

|                                     | Spatial Degree of Detail | Accuracy | Continuity | Integrity | Availability |
|-------------------------------------|--------------------------|----------|------------|-----------|--------------|
| GNSS-based<br>Road Charging Schemes | Zones                    | ****     | ***        | ***       | ****         |
|                                     | Road Segment             | ***      | ***        | ***       | ***          |
|                                     | Discrete Events          | ***      | **         | ***       | **           |

**Table 6.4:** Rating chart of the VLD performance in relation to the charging scheme's spatial degree of detail (with 1 star being lowest and 5 stars being highest).

As both the satellite visibility and the positioning accuracy have improved significantly, the results indicate that the main challenge related to vehicle location determination is not as often stated

due to positioning inaccuracies but instead to the high level of positioning interruptions mainly caused by GPS.

The many GPS gaps can affect the distance determination and hence charge computation, depending on both the frequency of gap occurrences and gap durations within a trip. The impact of GPS gaps is hence assessed in relation to the distance determination function in the following chapter.

## 6.5 Summary

In this chapter, an assessment of the vehicle location determination performance has been presented based on experimental work carried out in Copenhagen during 2008. There are several findings to be taken forward from this chapter.

Firstly, new methodologies have been presented for assessing both the positioning continuity and the time- and distance to first fix. The positioning continuity assessment methodology suggested by this thesis provides useful new information which supplements the accuracy, integrity and availability assessment methodology by [Ochieng and Sauer, 2002] very well. With this suggested methodology, there is a complete set of assessment methods for assessing the required navigation performance parameters for liability-critical road transport applications. This set of methods can be used to assess the vehicle location determination performance in future road charging trials or -systems.

Secondly, new results of vehicle location determination performance have been presented. The results from this chapter showed that the satellite visibility has improved significantly in Copenhagen between 2003–2008. Both the number of visible satellites and the horizontal dilution of precision have improved substantially, which means that the prerequisites to GNSS-based vehicle location determination have enhanced. In addition, the results showed that required navigation performance parameters for road transport applications were significantly better than compared to performance assessment results from London in 2002. While the

accuracy requirement in Copenhagen was partly met, the continuity and hence availability required for vehicle location determination suffer from severe gaps in the positioning data. These gaps were due to both satellite unavailability, caused by poor urban signal reception and long receiver acquisition times, and furthermore to the different technical problems and configuration faults which occurred during the experiment.



# Gap Influence on Driven Distance Determination

---

While the previous chapter identified the challenges of the vehicle location determination function and classified the different outages in the positioning information, this chapter presents an assessment of the driven distance determination tolerance towards the different positioning related outages. The assessment is conducted on the basis of a simulation methodology developed in this thesis.

## 7.1 Influence of Positioning Gaps on Determination of Driven Distance

This section analyzes the influence of positioning gaps on the determination of driven distance in GNSS-based road charging systems. As classified in Chapter 4, GNSS-based charging is either distance-based or distance-related. The gap influence on the distance determination in both types of charging schemes is important for the road charging system's ability to charge the road users correctly for their road usage.

In the literature, different studies have been conducted to assess the performance of distance determination in terms of different algorithms and filtering methodologies (refer to section 4.5). To the author's knowledge, no assessment of the positioning outages' influence on the two distance determination methodologies for GNSS-based road charging systems exists.

### 7.1.1 Simulation Methodology

In this section, a methodology for assessing the influence of continuity on the distance determination is developed. Based on simulations, the influence of gaps on the distance determination is assessed in relation to both distance-based and distance-related charging.

For the simulations, 25 trips with no interruptions in the positioning information were selected randomly from the collected data. Simulations of gaps were then applied to these selected trips, within different intervals and frequencies. The focus in this chapter is on the minor gaps of up to 10 minutes caused by satellite unavailability and long receiver acquisition times. The gap types used for the analyses in this thesis are given in Table 7.1.

|             | Interval   | Description                           |
|-------------|------------|---------------------------------------|
| Small gaps  | 2–10 sec   | Minor gaps up to 10 seconds           |
| Medium gaps | 11–60 sec  | Medium gap durations up to one minute |
| Large gaps  | 61–600 sec | Large gap durations up to 10 minutes  |

**Table 7.1:** Gap Types.

These gap types were applied with different frequencies in each of the 25 trips to represent the results of the vehicle location determination performance assessment in Chapter 6. The continuity results showed that the majority of gaps was within 25 seconds and that maximum gaps occurred within the 5-10 minutes interval. In addition, the results showed that the frequency of gaps on average was 22 per trip. Based on these figures, nine different scenarios were created for the simulations. Table 7.2 summarizes the simulation scenarios.



|                     | Small   | Medium   | Large  |
|---------------------|---|--|--|
| <b>Single gap</b>   | One small gap in each trip, less than 10 seconds<br>(S1)            | One medium gap in each trip, up to one minute<br>(M1)            | One large gap in each trip, up to 10 minutes<br>(L1)             |
| <b>Few gaps</b>     | Five small gaps in each trip, each gap less than 10 seconds<br>(S5) | Five medium gaps in each trip, each gap up to one minute<br>(M5) | Five large gaps in each trip, each gap up to 10 minutes<br>(L5)  |
| <b>Several gaps</b> | 10 small gaps in each trip, each gap less than 10 seconds<br>(S10)  | 10 medium gaps in each trip, each gap up to one minute<br>(M10)  | Not possible to simulate several large gaps within one trip<br>– |
| <b>Many gaps</b>    | 25 small gaps in each trip, each gap less than 10 seconds<br>(S25)  | Not possible to simulate many medium gaps within one trip<br>–   | Not possible to simulate many large gaps within one trip<br>–    |

**Table 7.2:** Simulation Scenarios.

The positioning data foundation for the distance determination is illustrated in Figure 7.1 on the next page for both the S5, M5, L5 data sets and the complete data set without any gaps in the positioning information. In the nine scenarios, the first and last positioning measurement were kept intact for all 25 trips.

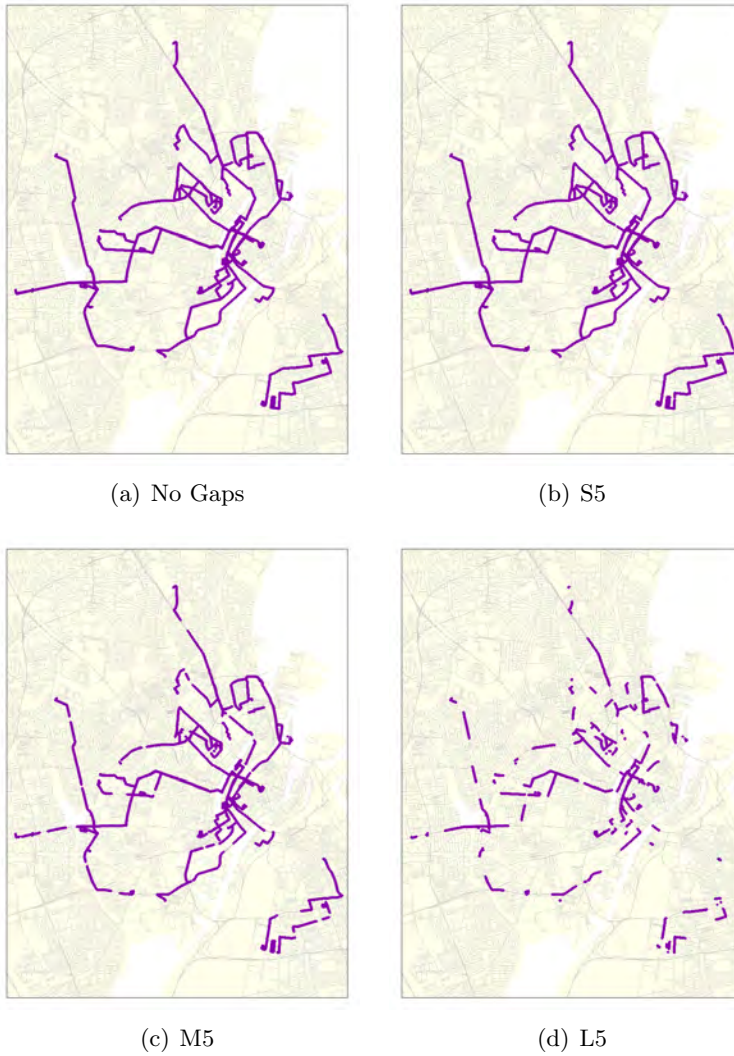
Based on these scenarios, the influence of gaps on the distance determination is assessed in relation to both distance-based and distance-related charging. The analyses and results are presented in the following sections.

### 7.1.2 Gap Tolerance in Distance-based Charging

In this section, the gap influence is determined for the distance-based charging based on a simplified distance determination methodology. For this distance-based analysis, the driven distance is determined based on the sum of Euclidian distances between the position measurements for each trip. In general, distance-based charging would include some kind of filtering algorithms to exclude positioning outliers in the data set, but for this analysis no filtering was applied in order to assess the tolerance of the simplest distance determination methodology. The driven distances are hence determined for all 25 trips in the nine scenarios and compared to the distances based on the complete data set.

Table 7.3 demonstrates the determined distance to the true distance expressed as percentage for all nine scenarios and each of the 25 trips.

The results show that small single gaps in the positioning measurements on average constitute 99.97 % of the true distance and thereby have a minor influence on the determination of distance driven in distance-based charging schemes. Several small gaps have more influence on the distance determination, which results in an underestimation of the driven distance due to the sum of shortest distances between the position measurements. In addition the results show that all the trips with small gaps in the position measurements constitute more than 99 % of the true distance.



**Figure 7.1:** 25 Trips within Different Simulated Gap Scenarios.

The medium gap durations have a significant impact on the distances in general and from the average figures the results indicate that a single or few medium gaps have more influence on the distance determination than many small gaps within a trip.

The large gap durations of up to 10 minutes have a severe influence on the distance determination both as a single gap or as a few gaps in a trip. In both scenarios, the distances are underestimated and in one case the distance determined only constitutes 60 % of the true distance. On average, the distances determined for the two large gap scenarios L1 and L5 constitute approximately 93 % and 87 % respectively.

| Trip    | S1     | S5     | S10   | S25   | M1     | M5    | M10   | L1     | L5    |
|---------|--------|--------|-------|-------|--------|-------|-------|--------|-------|
| 1       | 99.93  | 99.91  | 99.88 | 99.84 | 99.95  | 99.38 | 99.01 | 99.13  | 95.82 |
| 2       | 99.97  | 99.97  | 99.92 | 99.84 | 99.96  | 99.73 | 99.49 | 98.71  | 95.53 |
| 3       | 100.00 | 99.88  | 99.88 | 99.58 | 99.82  | 99.09 | 98.67 | 97.36  | 83.92 |
| 4       | 99.94  | 99.72  | 99.47 | 99.35 | 99.57  | 99.30 | 98.73 | 98.87  | 95.40 |
| 5       | 100.00 | 99.86  | 99.77 | 99.69 | 99.79  | 99.23 | 98.94 | 70.10  | 59.78 |
| 6       | 99.99  | 99.96  | 99.96 | 99.93 | 100.00 | 98.46 | 97.96 | 88.89  | 87.30 |
| 7       | 100.00 | 100.00 | 99.97 | 99.84 | 99.73  | 99.73 | 99.28 | 89.03  | 79.23 |
| 8       | 99.99  | 99.94  | 99.83 | 99.79 | 99.98  | 99.79 | 99.58 | 96.75  | 93.50 |
| 9       | 100.00 | 99.96  | 99.75 | 99.69 | 99.97  | 99.34 | 98.83 | 92.01  | 88.77 |
| 10      | 100.00 | 99.92  | 99.81 | 99.69 | 99.97  | 98.57 | 97.67 | 98.06  | 92.93 |
| 11      | 99.98  | 99.94  | 99.92 | 99.84 | 99.98  | 99.50 | 98.54 | 99.06  | 95.12 |
| 12      | 100.00 | 99.95  | 99.78 | 99.68 | 99.95  | 94.79 | 95.48 | 97.87  | 76.06 |
| 13      | 99.77  | 99.74  | 99.72 | 99.67 | 99.99  | 98.60 | 98.35 | 97.88  | 89.38 |
| 14      | 99.95  | 99.93  | 99.94 | 99.87 | 99.77  | 97.40 | 96.59 | 97.03  | 87.05 |
| 15      | 99.99  | 99.95  | 99.94 | 99.92 | 99.84  | 97.13 | 97.00 | 94.14  | 90.81 |
| 16      | 100.00 | 99.99  | 99.89 | 99.78 | 99.99  | 99.55 | 99.43 | 99.32  | 93.10 |
| 17      | 100.00 | 99.88  | 99.84 | 99.70 | 98.99  | 98.86 | 98.63 | 93.47  | 82.00 |
| 18      | 100.00 | 100.00 | 99.95 | 99.90 | 99.82  | 99.37 | 99.00 | 84.25  | 81.61 |
| 19      | 99.98  | 99.94  | 99.87 | 99.82 | 99.63  | 99.32 | 98.93 | 95.48  | 92.40 |
| 20      | 100.00 | 99.94  | 99.84 | 99.79 | 99.93  | 98.83 | 97.64 | 93.54  | 86.79 |
| 21      | 99.87  | 99.87  | 99.79 | 99.61 | 99.98  | 98.73 | 97.79 | 87.85  | 81.11 |
| 22      | 100.00 | 99.98  | 99.97 | 99.79 | 99.80  | 99.40 | 99.16 | 90.25  | 86.56 |
| 23      | 100.00 | 99.55  | 99.95 | 99.90 | 99.30  | 99.12 | 99.03 | 80.00  | 80.38 |
| 24      | 100.00 | 99.98  | 99.91 | 99.85 | 98.34  | 94.58 | 94.35 | 100.00 | 89.46 |
| 25      | 99.99  | 99.89  | 99.87 | 99.81 | 100.00 | 98.76 | 98.51 | 87.54  | 84.85 |
| Average | 99.97  | 99.91  | 99.86 | 99.77 | 99.76  | 98.66 | 98.26 | 93.06  | 86.76 |

**Table 7.3:** Determined Distances for Different Scenarios of Distance-based Charging.

In relation to the road charging performance requirements (refer to Chapter 4), the determination of the distance driven should be

kept within  $\pm 1\%$  of the truth. Table 7.4 shows the frequency of distance deviations in relation to the true distance.

|         | S1  | S5  | S10  | S25  | M1  | M5  | M10 | L1  | L5   |
|---------|-----|-----|------|------|-----|-----|-----|-----|------|
| 1%      | 0%  | 0%  | 0%   | 0%   | 0%  | 0%  | 0%  | 0%  | 0%   |
| 0%      | 40% | 4%  | 0%   | 0%   | 8%  | 0%  | 0%  | 4%  | 0%   |
| -1%     | 60% | 96% | 100% | 100% | 84% | 56% | 32% | 12% | 0%   |
| Outside | 0%  | 0%  | 0%   | 0%   | 8%  | 44% | 68% | 84% | 100% |

**Table 7.4:** Frequency of Distance Deviations in Distance-based Charging.

The results show that distance deviations, for the majority of trips with small gaps, are within the performance requirement of  $-1-0\%$  from the truth. In the medium scenarios, especially with few and several gaps respectively the distance deviations for several of the 25 trips fall outside, thereby indicating that the distance-based distance determination in these cases does not meet the performance requirement. For the large gap scenario L5, the distance deviations for the 25 trips are all less than  $-1\%$  of the true distance.

Comparing the distance determination results for the original 25 trips without gaps to the mileages determined by the OBUs, the results (refer to Table 7.5) show that the distance-based methodology determines longer distances (positive values). This may be due to fluctuations in the GPS position measurements which are not excluded by filtering techniques. The distance-based distance deviation varies between trips but is  $3.61\%$  on average. It should however be kept in mind, that the OBU mileage determination may be affected by data invalidity due to the technical problems described previously.

Compared to the distance determination results [MapFlow, 2007] from London, these results show a higher number of trips for which the distance is overestimated compared to the OBU mileage. However, if trips then have gaps in the position measurements, the driven distances based on the distance-determination will become shorter and the deviation hence minor. The distance-related results are discussed in the following section 7.1.3.

The results from this tolerance assessment show the influence of

| Trip    | Deviation Distance-based (%) | Deviation Distance-related (%) |
|---------|------------------------------|--------------------------------|
| 1       | 3,99                         | -3,52                          |
| 2       | 1,62                         | -7,14                          |
| 3       | 4,34                         | -10,27                         |
| 4       | 2,36                         | -0,83                          |
| 5       | 3,71                         | -23,14                         |
| 6       | 2,47                         | -11,22                         |
| 7       | 0,32                         | -2,53                          |
| 8       | 2,54                         | -5,52                          |
| 9       | 2,99                         | -4,39                          |
| 10      | 4,85                         | -8,78                          |
| 11      | 2,75                         | -0,66                          |
| 12      | 6,28                         | -14,57                         |
| 13      | 2,45                         | -1,66                          |
| 14      | 13,40                        | -20,39                         |
| 15      | 2,05                         | -5,42                          |
| 16      | 3,49                         | -3,38                          |
| 17      | 2,75                         | 6,91                           |
| 18      | 2,30                         | -8,73                          |
| 19      | 1,68                         | -6,09                          |
| 20      | 5,82                         | -4,41                          |
| 21      | 2,68                         | -0,96                          |
| 22      | 3,83                         | -3,45                          |
| 23      | 4,39                         | -4,15                          |
| 24      | 2,96                         | 5,36                           |
| 25      | 4,17                         | 2,65                           |
| Average | 3,61                         | -5,45                          |

**Table 7.5:** Distance Deviations in Percent of OBU Mileage.

different gap scenarios on the determination of driven distance in distance-based charging schemes. The distance-based distance determination is relatively unaffected by the occurrence of small gaps, while the occurrence of gap duration of up to one minute have a significant effect on the distance determination. Any occurrence of large gap durations may result in severe distance deviations. The total average for distance-based charging of all trips within the nine scenarios is 97.33 % of the true distance.

### 7.1.3 Gap Tolerance in Distance-related Charging

In this section, the gap tolerance is determined for the distance-related charging based on map-matching to the road network. The applied map-matching algorithm is developed by DTU Transport and described in [Nielsen and Jørgensen, 2004]. The driven distance is summarized for each trip based on the length of the road segments used. The driven distances are hence determined for all 25 trips in the nine scenarios and compared to the distances based on the complete data set.

Table 7.6 demonstrates the determined distance to the true distance expressed as percentage for all nine scenarios and each of the 25 trips.

The results show that small single gaps in the positioning measurements do not have any influence on the determination of the distance driven in distance-related charging schemes. Even with several or many small gaps within a trip, the distance determination is hardly influenced due to the map-matching algorithm estimating the distance in case of lack of positioning information. The distance determination constitutes 100 % of the true distance for the majority of trips in all small gap scenarios. On average, the distances determined for the small gap scenarios constitute between 99.22 % and 100 %.

While the distance determinations are hardly affected for single medium gap durations, few and several gap durations of up to one minute each have a significant influence on the distance determination. In both scenarios, the distances are generally underestimated

| Trip    | S1     | S5     | S10    | S25    | M1     | M5     | M10    | L1     | L5    |
|---------|--------|--------|--------|--------|--------|--------|--------|--------|-------|
| 1       | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 94.79  | 94.79  | 100.00 | 86.81 |
| 2       | 100.00 | 100.00 | 100.00 | 100.00 | 101.92 | 99.14  | 99.14  | 100.00 | 29.93 |
| 3       | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 97.44  | 97.44  | 100.00 | 12.36 |
| 4       | 100.00 | 100.00 | 100.00 | 97.13  | 100.00 | 100.00 | 100.13 | 100.00 | 72.31 |
| 5       | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 74.08  | 32.65  | 0.00  |
| 6       | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 88.52  | 72.06  | 77.99  | 55.16 |
| 7       | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 63.66  | 37.38 |
| 8       | 100.00 | 100.00 | 100.00 | 100.00 | 100.90 | 101.47 | 101.47 | 86.65  | 68.84 |
| 9       | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 99.34  | 58.41  | 49.55 |
| 10      | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 101.75 | 80.16  | 81.06  | 77.24 |
| 11      | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 91.97  | 100.00 | 35.35 |
| 12      | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 99.96  | 99.96  | 100.00 | 97.53 |
| 13      | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 93.12  | 70.81  | 92.16  | 57.12 |
| 14      | 100.00 | 85.09  | 85.09  | 85.09  | 100.00 | 100.00 | 89.55  | 96.89  | 90.81 |
| 15      | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 94.06  | 98.25  | 84.66  | 76.34 |
| 16      | 100.00 | 100.00 | 100.00 | 100.00 | 102.24 | 102.24 | 102.24 | 100.00 | 80.84 |
| 17      | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 89.26  | 58.09 |
| 18      | 100.00 | 100.00 | 100.00 | 100.65 | 100.00 | 104.32 | 92.76  | 69.65  | 40.24 |
| 19      | 100.00 | 100.00 | 100.00 | 99.94  | 100.00 | 101.33 | 101.33 | 93.09  | 72.70 |
| 20      | 100.00 | 100.00 | 100.00 | 100.00 | 98.84  | 95.37  | 65.80  | 87.38  | 77.64 |
| 21      | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 99.92  | 96.76 |
| 22      | 100.00 | 100.00 | 100.00 | 100.00 | 100.82 | 93.47  | 93.47  | 64.34  | 57.29 |
| 23      | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 96.09  | 0.00   | 0.00  |
| 24      | 100.00 | 100.00 | 100.00 | 100.00 | 96.04  | 96.04  | 97.68  | 98.07  | 93.06 |
| 25      | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 93.35  | 88.99  | 77.96 |
| Average | 100.00 | 99.22  | 99.22  | 99.25  | 99.94  | 99.11  | 93.38  | 81.80  | 65.51 |

**Table 7.6:** Distance Determination Results for Distance-related Charging.



and in one case the distance determined only constitutes 65 % of the true distance. On average, the distances determined for these two medium gap scenarios (M5 and M10) constitute approximately 99 % and 93 % respectively.

The results furthermore show that large continuous gap durations have a severe influence on the determination of the distance driven. In both large scenarios (L1 and L5) the distances are generally underestimated and as a result only constitute 81.8 % and 65.5 % in average. It is important to stress that in both cases, distance determination is not possible for all of the 25 trips. For two trips, map-matching to a road network on the basis of the positioning information including large gaps is not possible and as a consequence the distance cannot be determined.

With few large gaps in the positioning information during a trip, the results show that distance-related distance determination may only constitute down to 10-15 % of the true distance, if possible to determine at all.

In relation to meeting the road charging performance requirements (in Chapter 4), Table 7.7 shows the frequency of distance deviations in relation to  $\pm 1$  % of the true distance.

|         | S1   | S5  | S10 | S25 | M1  | M5  | M10 | L1  | L5   |
|---------|------|-----|-----|-----|-----|-----|-----|-----|------|
| 1%      | 0%   | 0%  | 0%  | 4%  | 8%  | 0%  | 4%  | 0%  | 0%   |
| 0%      | 100% | 96% | 96% | 84% | 76% | 40% | 12% | 28% | 0%   |
| -1%     | 0%   | 0%  | 0%  | 4%  | 0%  | 8%  | 12% | 4%  | 0%   |
| Outside | 0%   | 4%  | 4%  | 8%  | 16% | 52% | 72% | 68% | 100% |

**Table 7.7:** Frequency of Distance Deviations in Distance-related Charging.

The results show that the distance deviations, for the majority of trips with small gaps, are within the performance requirement of  $\pm 1$  % from the true distance. For several of the 25 trips with few or several medium gaps, the distance deviation falls outside, thereby indicating that the distance-based distance determination in these cases does not meet the performance requirement. For the large gap scenario L5, the distance deviations for the 25 trips are all less than -1 % of the true distance.

Comparing the distance determination results for the original 25 trips without gaps to the mileages determined by the OBUs, the results (refer to Table 7.5) show that the distance-related methodology mostly determines shorter distances (negative values). This is expected as map-matching of position measurements to the digital road network does not include position measurements before and after the first and last intersection in the trip. The distance-related distance deviation varies between the trips but is  $-5,45\%$  on average. The results show that the distance-related deviations are larger than the distance-based deviations. Compared to the distance determination results from London [MapFlow, 2007], these results have a less negative deviation average than the results based on TfL's own distance determination.

The results from this tolerance assessment show the influence of different gap scenarios on the determination of driven distance in distance-related charging schemes. The distance-related distance determination is unaffected by the occurrence of single small gaps. Due to the map-matching algorithm, the driven distance is estimated whenever there are small lacks of positioning information. However, for some trips these small gaps can have a greater influence on the distance determination than medium or large gaps. This hence indicates that the distance-related charging is more dependent on the spacial location of gaps in the positioning measurements. As with distance-based distance determination, medium gap durations have a significant influence on the distance driven, but any occurrence of large gap durations during a trip may result in severe distance deviations. The total average for distance-related charging of all trips within the nine scenarios is  $92.42\%$  of the true distance.

#### 7.1.4 Discussions on Gap Tolerance

The gap tolerance for distance determination in both distance-based and distance-related charging schemes has been analyzed in this section based on a simulation methodology. The gap tolerance of the distance determination in both types of charging schemes

is important for the road charging system's ability to charge the road users correctly for their road usage.

The results of this assessment show that small gaps have minor if any influence on the determination of the distance driven for both distance-based charging and distance-related charging. The distance-related distance determination is more robust towards the occurrence of small interruptions in the positioning information. Due to the map-matching of positions to the road network, the exact same distance is easier attained for distance-related charging. However, the distance-related charging is more dependent on the spatial location of gaps in the position measurements.

Medium gaps have significant influence on both charging methodologies. While the distance determinations are hardly affected for the single medium gap durations, few and several gap durations respectively of up to one minute each have a significant influence on the distance determinations for both charging methodologies. For the distance-based charging methodology, the results show that a single or few medium gaps have more influence on the distance determination than many small gaps within a trip. The distance-related charging methodology is more affected by medium gap durations and is poorer in reproducing the driven distance. Consequently, the determined distances deviate more from the true distance and in one case the distance determined only constitutes 65 % of the true distance.

For both charging methodologies, the large gap durations of up to 10 minutes have severe influence on the distance determination both as a single gap or as few gaps during a trip. In both large scenarios (L1 and L5) the distances are generally underestimated and deviate notably from the true distance. The results furthermore show that the distance-based distance determination is better at reproducing the true distance for trips with large gap durations. On average, the determined distances for the distance-related charging methodology constitute less of the true distance and more importantly, distance determination was not possible for all of the 25 trips. With few large gaps in the positioning information during a trip, the results show that distance-related distance determina-

tion may only constitute down to 10-15 % of the true distance, if possible to determine at all, while the distance-based distance determination constitutes down to 60 %. Furthermore, the total average for distance-based charging is 97.33 % and 92.42 % for the distance-related charging, which nearly indicates a 5 % difference between the two charging methodologies. Compared to the distance determination results from London [MapFlow, 2007] in section 4.5.3, the distance-based determination is comparable to the results from the best three OBUs. The distance-related charging is comparable to the average results based on TfL's own map-matching methodology.

The results furthermore show that for small gap durations the two charging methodologies both meet the performance requirement of  $\pm 1$  % deviation from the true distance. When medium gaps occur during trips, especially with few and several gaps the charging methodologies cannot meet the performance requirement for several trips as the distance deviation with both charging methodologies is outside the  $\pm 1$  % range. In the case of large gap durations, the distance deviations for the 25 trips are all less than -1 % of the true distance with both charging methodologies. The results are however affected positively by keeping the first and last position measurement in each trip. If these position measurements were excluded, the trip distances would naturally be shorter for both charging methodologies.

Compared to the results from London where the performance requirement could not be met, these results indicate a minor improvement although this is tested on a much smaller data set. When comparing the distances of the original 25 trips with the OBU mileage, the distance deviations become even larger for both charging methodologies.

The tolerance figures presented in this section are important for the implementation of GNSS-based road charging systems, in order to design a road charging process which can meet the performance requirement of less than  $\pm 1$  % deviation in 99 % of trips.

## 7.2 TTFF Influence on Distance Determination

In this section, a similar simulation methodology is applied to assess the influence of TTFF on the distance determination. Based on different simulations, the influence of TTFF on the distance determination is assessed in relation to both distance-based and distance-related charging. The TTFF influence is assessed separately as TTFF gaps in the literature are considered the main problem in relation to GNSS-based road charging systems [Zijderhand et al., 2006].

### 7.2.1 TTFF Simulation Methodology

For the TTFF simulations, the same 25 trips with no interruptions in the positioning information were selected from the collected data. Simulations of different TTFFs were then applied to these selected trips, within three different intervals. The TTFF intervals used for the analyses in this thesis are given in Table 7.8.

| TTFF   | Interval   | Description                           |
|--------|------------|---------------------------------------|
| Small  | 2–10 sec   | Minor TTFFs up to 10 seconds          |
| Medium | 11–60 sec  | Medium TTFF up to one minute          |
| Large  | 61–600 sec | Large TTFF durations up to 10 minutes |

**Table 7.8:** TTFF Intervals

TTFFs were simulated within these intervals in each of the 25 trips to represent the results of the TTFF assessment in Chapter 6. The TTFF results showed that the majority of gaps was within 10 seconds and that maximum TTFF occurred within the 5–10 minutes interval. Based on these figures, three different scenarios were created for the simulations. Table 7.9 describes the TTFF simulation scenarios.

Based on these scenarios, the influence of TTFFs on the distance

|             | Small  | Medium  | Large  |
|-------------|--|---|--|
| <b>TTFF</b> | A small<br>TTFF, less<br>than 10<br>seconds<br>(S) | A medium<br>TTFF gap,<br>up to one<br>minute<br>(M) | A large<br>TTFF gap,<br>up to 10<br>minutes<br>(L) |

**Table 7.9:** TTFF Simulation Scenarios.

determination is assessed in relation to both distance-based and distance-related charging. In all three scenarios, the last position measurement from the previous trip was kept as the first positioning measurement for all 25 trips as this was the default settings of the OBUs used in the experiment.

The analyses and results are presented in the following sections.

### 7.2.2 TTFF Tolerance in Distance-based Charging

In this section, the TTFF tolerance is determined for the distance-based charging based on the same simplified linear interpolation distance determination methodology as for the gap tolerance assessment in the previous section. The driven distances are hence determined for all 25 trips in the three scenarios and compare to the distances based on the complete data set.

Table 7.10 demonstrates the determined distance to the true distance expressed as percentage for all three scenarios and each of the 25 trips.

The results show that all three scenarios of simulated TTFFs have an influence on the distance determination in distance-based charging schemes, which in general results in underestimation of the determined distances.

Small TTFFs have a minor influence on the distance driven. The determined distances deviate up to approximately 4 % from the truth and the 25 trips on average constitute 99.43 % of the true

| Trip    | S      | M     | L     |
|---------|--------|-------|-------|
| 1       | 99.92  | 99.55 | 97.90 |
| 2       | 99.75  | 96.33 | 92.43 |
| 3       | 99.89  | 98.65 | 93.95 |
| 4       | 100.00 | 99.50 | 98.03 |
| 5       | 99.80  | 99.83 | 82.98 |
| 6       | 99.84  | 99.78 | 99.58 |
| 7       | 99.88  | 99.15 | 80.94 |
| 8       | 99.49  | 98.49 | 97.53 |
| 9       | 99.88  | 99.20 | 95.34 |
| 10      | 99.77  | 99.57 | 97.58 |
| 11      | 99.88  | 97.83 | 94.91 |
| 12      | 98.57  | 96.49 | 77.30 |
| 13      | 99.07  | 98.64 | 96.79 |
| 14      | 95.06  | 93.86 | 89.35 |
| 15      | 99.32  | 99.25 | 91.78 |
| 16      | 99.66  | 99.45 | 87.42 |
| 17      | 99.80  | 99.77 | 94.47 |
| 18      | 99.98  | 99.37 | 99.23 |
| 19      | 99.26  | 97.09 | 90.34 |
| 20      | 99.71  | 99.44 | 94.19 |
| 21      | 99.78  | 99.55 | 99.23 |
| 22      | 99.69  | 99.15 | 92.41 |
| 23      | 98.64  | 98.45 | 98.19 |
| 24      | 99.54  | 99.26 | 82.07 |
| 25      | 99.51  | 98.35 | 85.22 |
| Average | 99.43  | 98.64 | 92.37 |

**Table 7.10:** Distance Determination Results for Distance-based Charging.

distance. The medium TTFFs have a significant influence on the distance driven. The determined distances for trips with medium TTFF durations deviate up to approximately 6 % from the truth. On average, the 25 trips constitute 98.64 % of the true distance.

In addition the results show that all trips with large TTFFs of up to 10 minute duration deviate from the true distance. The determined distances for large TTFFs deviate up to approximately 22 % from the truth and the 25 trips on average constitute 92.37 % of the true distance.

Compared to the single gap results from Section 7.1.2, the TTFF results show that the distance-based distance determination is generally more influenced by TTFF gaps than any single gaps during a trip.

### 7.2.3 TTFF Tolerance in Distance-related Charging

In this section, the TTFF tolerance is determined for the distance-related charging. The methodology used for distance determination is based on the same map-matching methodology (as described in Section 7.1.3), relating the position measurements to the road network and summarizing the length of the road segments used. The driven distances are hence determined for all 25 trips in the three scenarios and compared to the distances based on the complete data set.

Table 7.11 demonstrates the determined distance to the true distance expressed as percentage for all three scenarios and each of the 25 trips.

The results show that all three scenarios of simulated TTFFs have an influence on the distance determination in distance-related charging schemes, which again results in a general underestimation of the determined distances.

As with the single gaps in the previous assessment, the small TTFFs hardly deviate in the distance determination, except for a single trip which deviates approximately 2 % from the truth. Consequently, the 25 trips including small TTFFs in average con-



| Trip           | S            | M            | L            |
|----------------|--------------|--------------|--------------|
| 1              | 100.00       | 100.00       | 97.72        |
| 2              | 100.00       | 96.80        | 87.58        |
| 3              | 100.00       | 97.44        | 80.20        |
| 4              | 100.00       | 97.31        | 84.69        |
| 5              | 100.00       | 100.00       | 78.18        |
| 6              | 100.00       | 100.00       | 97.54        |
| 7              | 100.00       | 92.67        | 54.21        |
| 8              | 100.00       | 78.78        | 92.85        |
| 9              | 100.00       | 100.00       | 95.53        |
| 10             | 100.00       | 100.00       | 81.06        |
| 11             | 100.00       | 94.76        | 47.52        |
| 12             | 100.00       | 98.65        | 86.50        |
| 13             | 100.00       | 100.00       | 84.33        |
| 14             | 100.00       | 100.00       | 98.13        |
| 15             | 98.25        | 98.25        | 83.46        |
| 16             | 100.00       | 100.00       | 51.57        |
| 17             | 100.00       | 98.51        | 93.90        |
| 18             | 100.00       | 104.32       | 104.32       |
| 19             | 100.00       | 98.98        | 73.17        |
| 20             | 100.00       | 100.00       | 90.26        |
| 21             | 100.00       | 90.80        | 90.80        |
| 22             | 100.00       | 97.05        | 83.42        |
| 23             | 100.00       | 100.00       | 100.00       |
| 24             | 100.00       | 100.00       | 61.49        |
| 25             | 100.00       | 88.17        | 76.59        |
| <b>Average</b> | <b>99.93</b> | <b>97.30</b> | <b>83.00</b> |

**Table 7.11:** Distance Determination Results for Distance-related Charging.

stitute 99.93 % of the true distance. On the other hand, the medium TTFFs have a significant influence on the distance driven in distance-related charging schemes. The determined distances for trips with medium TTFF durations deviate up to approximately 21 % from the truth. On average, the 25 trips constitute 97.3 % of the true distance.

For all trips with large TTFFs of up to 10 minutes' duration, the determined distance deviates from the true distance. The determined distances for large TTFFs deviate up to more than 50 % from the truth, resulting in that the 25 trips on average constitute 83 % of the true distance. The results show that these large TTFFs have a severe influence on the distance determination for distance-related charging schemes.

Compared to the single gap results from Section 7.1.3, the TTFF results are relatively similar, which indicate that the distance-related distance determination is equally influenced by the TTFF and a single gap during a trip.

#### 7.2.4 Discussions on TTFF Tolerance

The TTFF tolerance for distance determination in both distance-based and distance-related charging schemes has been analyzed in this section based on a simulation methodology. The TTFF tolerance of the distance determination in both types of charging schemes is important for the road charging system's ability to reproduce the distance driven and charge the road users correctly for their road usage.

The results of this assessment show that TTFFs within all three duration intervals have a influence on the distance determination, resulting in a general underestimation of the determined distances. For both charging methodologies, small TTFFs hardly have any influence on the distance determination. The distance-related distance determination is again found to more robust towards these small interruptions in the positioning information than the distance-based methodology.

The medium TTFFs have a more significant influence on the distance driven. For distance-based charging, the determined distances for trips with medium TTFF durations deviate up to approximately 6 % of the truth. On average, the 25 trips constitute 98.64 % of the true distance. The distance-related charging methodology is more affected by medium TTFF durations and is poorer in reproducing the driven distance. Consequently, the determined distances deviate up to approximately 21 % from the truth. On average, the 25 trips constitute 97.3 % of the true distance.

In addition the results show that for both charging methodologies, all trips with large TTFFs of up to 10 minutes' duration deviate from the true distance. For the distance-based charging, the determined distances for large TTFFs deviate up to approximately 22 % of the truth and the 25 trips in average constitute 92.37 % of the true distance. The results furthermore show that the distance-based distance determination is better at reproducing the true distance for trips with large gap durations. The determined distances for large TTFFs with the distance-related methodology deviate up to more than 50 % of the truth, resulting in that the 25 trips on average constitute 83 % of the true distance. The large TTFFs consequently have a severe influence on the distance determination for especially distance-related charging schemes.

In addition, the TTFF tolerance assessment showed that the distance-based distance determination is generally more influenced by TTFF gaps than other single gaps during a trip. The distance-related distance determination was found to be equally influenced by TTFFs and other single gaps during a trip.

### 7.3 Gap Influence Results

Gathering the results from this assessment in an event tree, the probabilities of the different outcomes for distance-based and distance-related charging can be demonstrated. The Event Tree Analysis (ETA) is an analysis technique for identifying and evaluating the

sequence of events. The probability of a specific outcome is then calculated by multiplying the event probabilities in the path. The event tree is performed with RAM Commander's Event Tree Analysis Software Module [A.L.D. Engineering, 2010].

The event tree illustrates the possibility of providing correct charges in case of different gap durations based on the gap duration distribution found in trips in Chapter 6. The gap distribution is based on the maximum continuous gap in the trip and the distance determination success rate is based on the average deviation results within the three different gap duration scenarios (refer to Table 7.4 and Table 7.7). This event tree analysis however does not include the combination of small, medium and large gaps within a trip, but is based on the average of a single, few or many gaps within each gap duration category. The TTFFs are in addition included as regular gaps and all gap outliers are furthermore excluded from the distance determination. Hence, the outcome percentages are not exact but are overall estimates to demonstrate the distribution of success and failure for distance-based charging.

### 7.3.1 Distance-based Charging

The event tree in Figure 7.2 illustrates the probabilities for different charging outcomes for distance-based charging schemes.

The figure demonstrates that for the majority of trips which have small gaps in the positioning, the distance-based charging results in a distance deviation less than  $\pm 1\%$  for 63.56 % of the trips because the probability of distance determination success was 100 % for all trips with small gaps. For trips with no gaps the distance determination is presumed to be less than  $\pm 1\%$  for all the trips. The event tree demonstrates that for the majority of trips, the road charging outcome results in correct charges. However for trips with large gaps, the majority of distance determinations will result in incorrect charging. Summarized, the distance-based charging will result in correct charging with less than  $\pm 1\%$  deviation for 99.30 % of all trips.

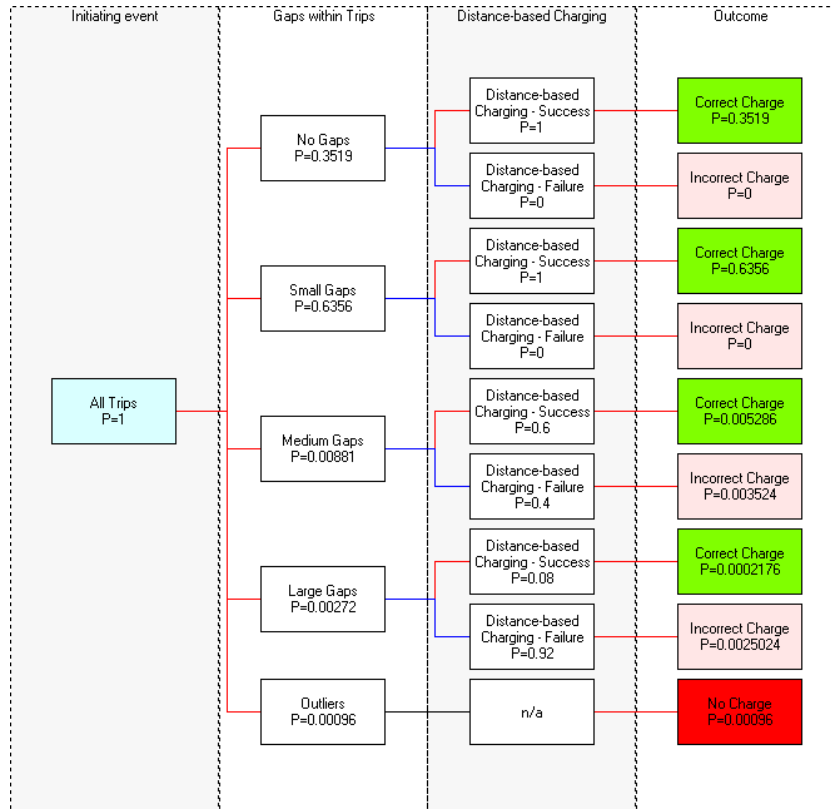
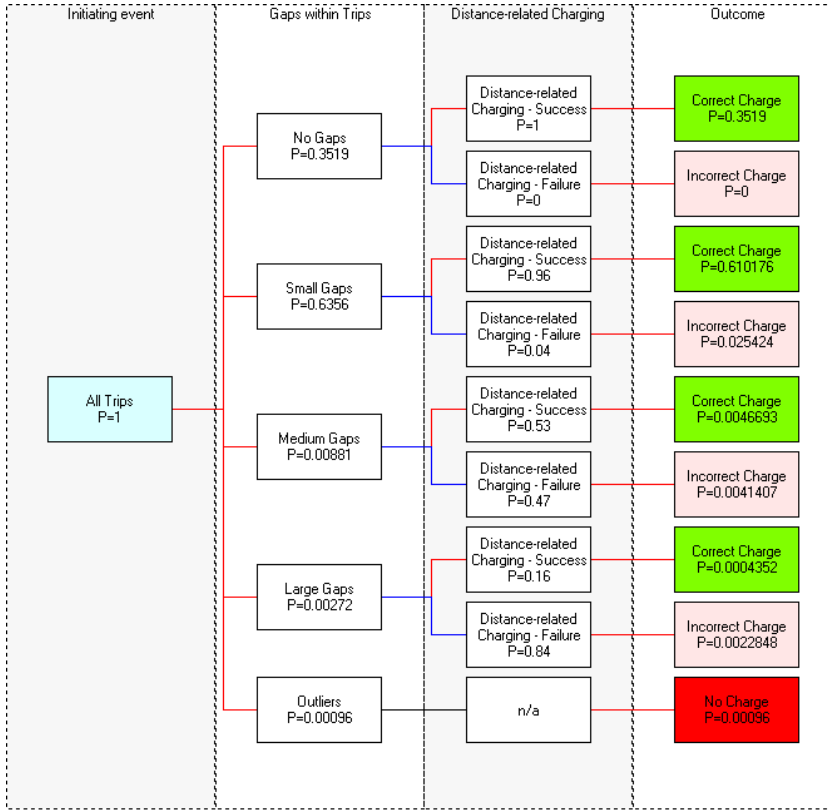


Figure 7.2: Event Tree for Distance-based Charging.

### 7.3.2 Distance-related Charging

The event tree in Figure 7.3 illustrates the probabilities of different charging outcomes for distance-related charging schemes.



**Figure 7.3:** Event Tree for Distance-related Charging.

The event tree demonstrates that for the majority of trips which have small gaps in the positioning, the distance-based charging results in a distance deviation less than  $\pm 1\%$  for 61.02 % of the trips as the average success rate for distance determination was 96 % for all trips with small gaps. This is a little lower success rate than for the distance-based results in Figure 7.2. For trips with large gaps in the positioning, the distance determination success rate is however higher than for distance-based charging.

The event tree demonstrates that for the majority of trips the road charging outcome results in correct charges. Summarized, the distance-based charging will result in correct charging with less than  $\pm 1\%$  deviation for 96.71 % of all trips.

## 7.4 Discussions on Gap Influence

The simulation analyses of the gap influence on the driven distance determination has showed that the distance determination function is relatively robust against small gaps in the positioning. The results showed that both the distance-based and distance-related charging small gaps have minor if any influence on the determination of distance. The distance-related distance determination is more robust towards the occurrence of small interruptions in the positioning information due to both satellite unavailability and time to first fix. In addition, the results demonstrated that due to map-matching of positions to the road network, the exact same distance is more easily attained for distance-related charging. However, the distance-related charging is more dependent of the spatial location of gaps in the position measurements.

Secondly, it was found that for both charging methodologies, the large gap durations of up to 10 minutes have severe influence on the distance determination both as a single gap or as few gaps during a trip. Both in situations with single or few large gaps, the distances generally are underestimated and deviate notably from the true distance. The results furthermore show that the distance-based distance determination is better at reproducing the true distance for trips with large gap durations. On average, the determined distances for the distance-related charging methodology constitute less of the true distance and more importantly, distance determination was not possible for all of the 25 trips.

In addition, the results showed that for small gap durations the two charging methodologies both meet the performance requirement of  $\pm 1\%$  deviation from the true distance. In the case of large gap durations, the distance deviations for the 25 trips are all less than

-1 % of the true distance with both charging methodologies. This means that both charging methodologies are robust towards small gaps and that in case of large gaps the road users are not over-charged. The importance of these results is that for the majority of trips the distance driven can be determined with less than  $\pm 1$  % distance deviation as the occurrence of small gaps is most frequent during trips. It is however important to keep in mind, that the presented results from this chapter depend on both the truth of the digital road network and the map-matching algorithm used for the distance determination. For both charging methodologies, many different algorithms exist and the performance of these varies as seen from the TfL Trial analyses. Although the distance deviation is more than  $\pm 1$  % from the OBU mileage for both charging methodologies, improvement is found compared to the distance deviation results from the London TfL Trials.

Finally, the probabilities of different outcomes were illustrated for both charging methodologies. The event trees presented in this thesis showed that when gathering the results in event trees the majority of trips will result in correct charges. Although the figures are not exact, they demonstrate the distribution of correct charging with less than  $\pm 1$  % deviation for the two charging methodologies. The results showed that while large gaps have a higher influence in distance-based charging, the distance-based methodology on average results in less distance deviation from the truth for small and medium gaps.

The presented figures are important in relation to the design of GNSS-based road charging systems, as the results demonstrate the gap influence on the two distance determination methodologies. While the distance-related determination is more robust towards small interruptions in the positioning measurements and better in attaining the exact same distance for the exact same trip, the total average constituting the true distance is however higher for distance-based charging. The TTFF and gap tolerance of the distance determination in both types of charging schemes is important for the road charging system's ability to charge the road users correctly for their road usage.



## 7.5 Summary

In this chapter, an assessment of the distance determination performance has been presented. There are important findings to be taken forward from this chapter.

This chapter has provided a new assessment methodology for assessing the gap influence on the driven distance determination based on simulation. Although the methodology is fairly simple, the methodology provides new valuable results on gap influence which to the author's knowledge does not exist in the literature. The gap influence results were in addition summarized for both charging methodologies based on the results from this PhD work and the probabilities of different charging outcomes were demonstrated.



# Dependability of GNSS-based Road Charging Systems

---

The performance assessments in the previous chapters have presented both the technical challenges during the experiment and the challenges of vehicle location determination and driven distance determination. These different challenges have different impact on the overall system dependability and should therefore be considered during the design of GNSS-based road charging systems. As dependability is an important requirement for a GNSS-based road charging system, the system must provide fair charging and gain user trust by ensuring system reliability and liability. This chapter discusses the impact of the assessment results in relation to system dependability. Hereafter different perspectives are discussed in relation to providing fault tolerance road charging, and finally this chapter provides guidelines for future GNSS-based road charging trials and GNSS-based road charging in Denmark.

## 8.1 Dependability Risk Assessment

The preceding chapters have highlighted the complexity of GNSS-based road charging systems performing many different functions by means of various technologies. GNSS-based road charging systems often involve automated processes and interaction between components and different interfaces. These complex systems rely on the performance of every single element as one failure can result in failure of the whole system and affect the dependability of the road charging system. Reliability, integrity, accuracy and availability are important performance requirements for GNSS-based road charging systems in order to provide a dependable road charging service that is acceptable to governments, road providers and the road users who will rely on them. Generally, road charging systems require high dependability to ensure the road users trust and avoid economic losses. This high degree of dependability gives the road users a good sense of credibility towards the road charging system, as it is important for the road users to know that they are being correctly charged for their road usage.

The results from the assessments conducted in this thesis demonstrate that although significant performance improvements have happened during the last five years, there are significant challenges to overcome in relation to implementation and operation of GNSS-based road charging systems. The results presented show the existing performance level of the vehicle location determination and driven distance determination for GNSS-based road charging systems based on state of the art technology. The results presented in this thesis are all based on the collected data in its original form. Data has thereby been represented in its true form as it would be used as input for the automated charge calculation process in a road charging system. The many challenges and results have different impact on the dependability of GNSS-based road charging systems. In the following the results found from the assessments in this thesis are discussed in relation to the dependability. The dependability risk assessment presented in the following is summarized in [Figure 8.1 on page 251](#).

### 8.1.1 Data Reliability

The assessment of the data reliability (in Chapter 5) showed a severe level of unreliability due to technical problems during the experiment which resulted in a high level of data invalidity and deficiency. For the same reason, the collected data was also found to be inaccurate and incomplete in its form for the purpose of charging road users for their road usage. The data included incorrect information as well as many incorrect data records that put a lot of unnecessary stress on the system thereby affecting the system's overall performance. The high percentage of invalid trips registered with several records, but without distance or duration, affects the back-office performance as these invalid data records are being both transmitted and processed in the system. The extra load of invalid data records may result in capacity or memory problems leading to for instance server break-downs. The invalid trips which do have a distance due to position fluctuations could result in incorrect charging if not filtered out of the data prior to the driven distance determination. This emphasizes the need for a data processing function prior to the distance determination and road charge calculation process.

A more severe concern was caused by the occurrence of overlapping trips in the data set. Even though the percentage of overlapping trips was small, the severity of charging road users for trips in different geographic locations within the same time frame is alarming. As both overlapping trips were registered normally, automated charging processes would have difficulties in verifying which trip is the valid one to charge. However, filtering techniques could be applied to verify that trips performed by the same road user have a logical connection with respect to the different trips driven. This example of data invalidity is very important to ensure system liability and emphasizes the need for an enforcement system which can help to verify trip activity and produce evidence in case of complaints from the road users.

In addition the results showed a great difference in the performance of the OBUs. Although the OBUs were from the same

vendor, there was a significant difference between how well each OBU performed. This of course can be due to hardware or software problems for specific OBUs, but the overall concern from this is the road charging system's ability to provide equally fair charging for all road users. Basically all OBUs should be able to provide equal performance in order to ensure that all road users will be charged equally for the same trips. The results furthermore rise the question of how to detect and handle incorrect working OBUs. Generally, incorrect working OBUs can be due to both technical problems and intentional tampering (e.g. jamming) with the units for which reason quick and timely detection and handling of such OBUs is essential for the system dependability.

The challenge of ensuring data reliability is therefore both to prevent the technical problems resulting in these data errors but also to consider the handling of the data invalidity so that automated data processing can replace manual error detection and correction work. The handling could include different filtering techniques and methodologies in a data processing function prior to the distance determination and charge calculation supported by an enforcement system.

### **8.1.2 Vehicle Location Determination Performance**

The assessment of the vehicle location determination function (in Chapter 6) showed a high level of unavailability. A large percentage of the unavailability was due to technical problems resulting in system downtime gaps and gaps caused by incorrect system configuration. Although these gaps caused by system downtime and configuration faults constituted a large percentage of the vehicle location determination unavailability, these gaps only constituted a small percentage of the total number of gaps. The majority of gaps was found to be less than 25 seconds and in most trips the total duration of the gaps was between 2–5 seconds. Although these minor gaps occurred frequently during the trips, they only constitute a small risk with respect to the system dependability as the trips easily can be reproduced for charge calculation. How-

ever, both the medium and large GPS gaps can result in poor trip reproduction and therefore constitute a more significant risk with respect to system dependability. The same conclusions apply for the TTFF gaps although the dependability risk is slightly higher with TTFF gaps as the driven distance determination proved to be more influenced by TTFF gaps.

In addition the results showed that the positioning accuracy no longer threatens the required navigation performance in relation to land applications. From the literature study (in Chapter 4), the results show that the average obtainable position accuracy in dense urban areas in Europe is approximately 6–12 meters. The positioning accuracy has improved significantly due to the improved satellite visibility and now partly satisfies the requirements for liability-critical road transport applications in Copenhagen. 99.85 % of the position measurements are within 100 meters from the center of the road, which is a significant improvement compared with similar results from for example London. In 81 % of the system uptime there are more than five visible satellites from which the redundant observation can be used to give timely system warnings.

The improved satellite visibility is the result of both improved satellite conditions and a development in GNSS receivers which generally use HSGPS receivers nowadays. The positioning accuracy is therefore no longer considered a serious risk with respect to the system dependability although positioning outliers can always occur due to the different error sources. However in order to determine vehicle locations in dense urban areas where parallel roads are close to each other an accuracy level of 20–30 meters is necessary to distinguish between roads. This in combination with the more densely build up areas in city centres means that positioning accuracy is a greater dependability risk for cumulative charging schemes with spatial degree of detail at road segment level. For cumulative charging schemes with spatial degree of detail at zone level, the risk can be minimized by establishing buffers at the zone borders. In order to locate the vehicle correctly in 99 %, the results showed that buffers of 100 meters are necessary for Copenhagen.

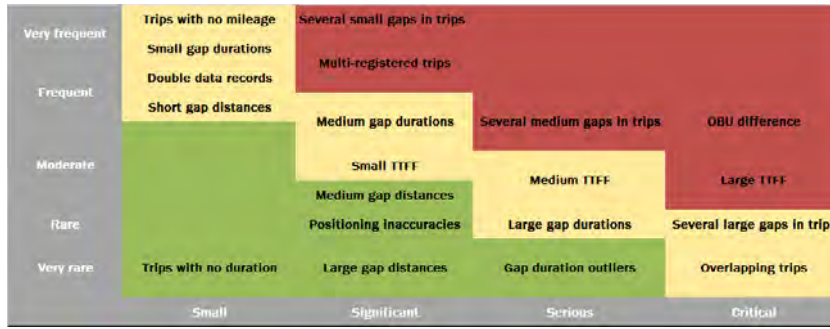
Furthermore, the results showed that in 84 % of the trips, the positioning ratio constitutes more than 90 % of the trip. In relation to the ability of reproducing the distance driven, the maximum continuous gap duration is of interest. Here the results from the assessments presented in this thesis show that 90 % of the trips have maximum continuous gap durations of less than 60 seconds. This is especially interesting for choosing supporting dead-reckoning systems for the vehicle location determination function. Most of today's available dead-reckoning systems can support the vehicle location determination up to 60 continuous seconds, which means that gap durations for the last 10 % of trips hence should be addressed in other ways. The large continuous gaps are hence a serious risk for the system dependability. The missing distance determination during these gaps is important in relation to the ability of reproducing the total distance driven. The results showed that in 90 % of the trips, the gap distance ratio constitutes up to 30 % of the trip. The large gap distances are therefore a significant risk as these are the distances which become estimates in the trip reproduction. Furthermore, the gap distance results showed that 99 % of all the gaps result in distances less than 200 meters. The average gap distance excluding outliers was found to be 15 meters.

The challenge of meeting the required navigation performance parameters and ensuring dependable vehicle location determination for the purpose of road charging is to reduce the number of GPS gaps and prevent the gaps caused by system downtime and configuration faults.

Figure 8.1 illustrates a qualitative dependability risk matrix for the vehicle location determination function based on the results found in this thesis. The figure demonstrates the different discussed issues in relation to their occurrence frequency and consequence severity.

The figure demonstrates that the vehicle location determination function is subject to dependability risk hence the consequences exceed the acceptable green level. Issues within the red level are critical for the system dependability and precautions should be made to decreased the applied risk. Issues within the yellow level





**Figure 8.1:** Dependability Risk Matrix for the VLD Function.

are less critical but still severe for the system dependability. Hence, especially the upper yellow level should be thoroughly considered in the design of GNSS-based road charging systems.

The dependability risk matrix provides a good indicator of the dependability threats towards GNSS-based road charging systems based on the results found in this thesis. It should however be noted that the dependability matrix is even more complex when including the additional threats (e.g. jamming) towards the system which have not been included in this PhD research.

### 8.1.3 Influence on Driven Distance Determination

The simulation analyses of the gap influence on the driven distance determination (in Chapter 7) showed that the distance determination function is relatively robust against small gaps in the positioning. Whether the distance determination is distance-based or distance-related, the driven distance can be determined for both minor gaps and minor TTFFs of less than 10 seconds. Even with several or many small gaps in a trip, the driven distance can be determined for the majority of trips with less than  $\pm 1\%$  deviation from the truth. With several medium and large gaps in the trips, both distance determination methods have trouble in reproducing the driven distances with distance deviations more than  $\pm 1\%$ . The importance of these results is that for the majority of trips the

distance driven can be determined with less than  $\pm 1\%$  distance deviation as the occurrence of small gaps is most frequent in trips. The simulation results (summarized in Table 8.1) in addition show that the majority of trips will result in correct charging.

|                  | Distance-based | Distance-related |
|------------------|----------------|------------------|
| Correct charge   | 99,30%         | 96,72%           |
| Incorrect charge | 0,60%          | 3,18%            |
| No charge        | 0,10%          | 0,10%            |

**Table 8.1:** Summary of Distance Determination Performance.

The results presented from the simulation are simplified and based on the experimental results. Hence they do not present the exact values as in a real-life setup, but they do give an indication of the current performance level. It is however important to keep focus on the last small percentage of trips for which the distance deviation is more than  $\pm 1\%$ , in order to reduce the number of trips that hence must be charged based on alternative methodologies. Road charging based on alternative methodologies will, all things being equal, result in undercharging and thereby become a cost for the road charging system.

The challenge of meeting the requirement of 99 % of trips with only  $\pm 1\%$  deviation from the driven distance is both to reduce large maximum continuous gaps as these are the most difficult to reproduce and to improve the methodologies for determining the distance driven. The results from London (refer to Chapter 4) underlined the importance of choosing the right combination of OBU and distance determination methodology in order to obtain the best results for the road charging process. The results presented in this thesis are based on simple methods but many different methods exist for both distance-based and distance-related charging which include more advanced algorithms and filtering techniques.

## 8.2 Fault Tolerant Road Charging Systems

There are different possibilities to reduce this last percentage of trips for which the distance deviates more than  $\pm 1\%$  from the truth. This small percentage is very important for the system as these trips require alternative charging methodologies which give rise to more manual data work, more validation of trips, increased handling of complaints etc. Hence these trips can, at the end of the day, become very costly for the road charging system both economically and in terms of system credibility.

In the literature, both internal and external augmentation systems have shown potential of supporting the vehicle location determination function in better positioning results. Although it appears from the literature study that there are not many comparable tests of the use and the possibilities of internal augmentation systems in connection with road charging systems, the few studies that have been carried out indicate that results are promising for the use of dead-reckoning systems for GNSS-based road charging. The use of both dead-reckoning systems, data assistance from overlay services and cellular network, application augments, and complementary technologies can provide additional support for the vehicle location determination function ([Zijderhand et al., 2006] and [Pickford and Blythe, 2006] provides a comprehensive review). It is however unrealistic to believe that the vehicle location determination function in the near future will be able to provide 100 % correct positioning as the positioning very much depends on both spatial conditions and external conditions such as soft- and hardware faults, human errors, jamming etc. The focus of the system performance concerns should therefore be placed on how future GNSS-based road charging system can be design to work reliably **with** the occurrence of both data invalidity and data deficiency.

In electrical engineering, fault tolerant design is a design that by redundancy enables a system to continue operation, when some part of the system fails [Avizienis et al., 2000]. The fault tolerance methods deal with how to deliver correct service in the presence of faults and are therefore a very important means for dependability

as it allows the user to rely on the system regardless of the faults [Deconinck and Peperstraete, 1997]. Regarding GNSS-based road charging systems, the questions of concern should hence be:

- Which procedures can be implemented to ensure dependable system operation despite the occurrence of faults and shortcomings?
- Which filtering techniques and methodologies can be integrated into the back-office system to ensure correct charging in case of faults?
- Which technology or methodologies can be developed to give timely system warnings before the faults happen?
- And what kind of applications should be implemented to protect both the system and the end-user from fraud and misuse?

...and many more. Fault tolerance is generally implemented by error detection and subsequent system recovery methods.

The fault tolerant design should be implemented both at the component and function level for the road charging process which is the most liability-critical part of the road charging system. However, in order to provide a dependable road charging system, the fault tolerant design should also be considered at system level – preferably quite early in the system design process. Based on the conceptual system architecture (developed in Chapter 3), fault forecasting methodologies can be used to assess and predict faults and failures both at the functional and component levels. The consequences and their severity regarding system dependability can hence be handled prior to the detailed system design.

### **8.2.1 Fault Tolerant Road Charging Process**

The road charging process (refer to Chapter 4) consists of many different technologies and procedures which together shall ensure that the road users are charged correctly for their road usage.

To ensure high dependability of the road charging process, fault tolerant design should hence be considered in relation to many different components and functionalities within the process.

The inclusion of some kind of enforcement system is a well-known fault tolerant design implementation within the road charging process. The enforcement system is a redundant method of providing knowledge of the road users road usage when their driven trips cannot be reproduced. Although, the enforcement system provides vehicle location knowledge at a reduced level, it contributes with useful information to the road charging process rather than failing completely. In the same way, dead-reckoning system integration in the OBU is also a well-known fault tolerant design solution. The dead-reckoning system provides position estimates in the case of satellite unavailability and supports the vehicle location determination function. Although the DR position estimates have a lower level of accuracy, it provides useful estimates to the trip reproduction in the case of positioning gaps.

Likewise, fault tolerance should be included in the driven distance determination. As seen from Chapter 7, the distance-related charging methodology sometimes fails to determine the driven distance. In these cases, the distance-based charging methodology can be used as a redundant system to provide distance estimates. Basically, distance-related distances should be shorter than for distance-based distance determination. However, if the distance-related distance deviates notably (e.g. more than 50 %) from the distance-based distance, the system cheats itself by undercharging the road user and should instead use the distance-based distance. Opposite, if the distance-related distance is longer than the distance-based one (e.i.  $\pm 1$  %), the vehicle location data should be verified as the system otherwise overcharges the road user. In more severe cases of data loss, the vehicle location determination function could for instance in addition be supported by data readings from the vehicle's CANbus<sup>1</sup>.

The main objective of fault tolerant design within the road charg-

---

<sup>1</sup>CANbus is a serial communication system used on many motor vehicles to connect individual systems and sensors.

ing process is to ensure fair charging of the road users. This means that redundant systems, procedures and components should be implemented to ensure that when fault and failures occur within the road charging process, the road charge foundation will still be dependable and provide fair results towards both the road users and the road charging system.

### **8.2.2 Fault Tolerant System Design**

However, to provide a dependable road charging system, fault tolerant design must be implemented to ensure maximum system uptime. If the road users often experience system downtime and configuration faults, it will affect the road users' trust and acceptability of the system which in the end can have severe impacts on the system credibility.

Fault tolerance should therefore be considered in terms of all subsystems, procedures and components which can result in system downtime. This may include server break-downs, faulty on/offline procedures and (web-) interfaces in the back-office solution, communication failures, hardware/software failures and also human errors. In addition, fault tolerant design should be considered in all main functions including both billing, system and user service management to ensure a dependable road charging system. The fault-tolerant solutions should be able to handle several possible failures, including both temporary or permanent failures within the system and also physical damage or other flaws introduced to the system from an outside source.

The essential ways of achieving fault tolerant design include dependability enhancing techniques that are used during the validation of components to estimate the presence of faults and the occurrence and consequences of failures. This includes both reliability prediction methodologies and several methods for reliability assessment without prediction which can be conducted to identify and analyze the failure modes of a system and support the system development. [Foucher et al., 2002] provides a review of reliability prediction methods while [Düpow and Blount, 1997] provide a list

of commonly used reliability assessment/analysis methods.

The fault tolerant design can provide dramatic improvements in system dependability and lead to a substantial reduction in charging failures as a consequence of fewer disabling system failures.

## 8.3 Proposed Guidelines

Based on the several findings of this thesis, some general guidelines can be formulated for future GNSS-based road charging systems. The proposed guidelines described in the following address both GNSS-based road charging trials in general and a future GNSS-based road charging system in Denmark.

### 8.3.1 GNSS-based Road Charging Trials

When completing a trial or a technical experiment, there are always new experiences gained. Some of these experiences are of course trial specific but most of them are valuable experiences that one would wish were known prior to the experiment. These experiences are important to share as proposed guidelines, so that others designing and conducting GNSS-based trials and experiments can benefit from these valuable lessons learned.

The lessons learned from the experiment and work conducted in this PhD study are manifold. Table 8.2 lists the most important ones as guidelines proposed by this thesis.

The guidelines proposed for GNSS-based road charging trials focus on the experimental design and the trial execution. The previous chapters have described the technical challenges, problems and considerations during the experiment which have formed the basis for the guidelines presented.

| Task                                       | Focus Area              | Guidelines  |
|--|-------------------------|---|
| <b>Experimental Design &amp; Execution</b> | <b>Participants</b>     | <ul style="list-style-type: none"> <li>• Attention to difficulties in recruiting and retaining participants</li> <li>• Monetary value, gift or contest with prize is necessary to get people to participate in trials</li> </ul>  |
|  | <b>OBU installation</b> | <ul style="list-style-type: none"> <li>• Different OBU placement requirements</li> <li>• OBU mounting security</li> <li>• Insurance problems if technical installations have been done by unauthorized garages</li> <li>• Permission requirement from the police</li> </ul> |
|  | <b>Communication</b>    | <ul style="list-style-type: none"> <li>• GPRS continuous data transmission</li> <li>• SIM cards must be unlocked and open during the whole experiment period</li> <li>• Attention to incoming text messages</li> </ul>  |
|  | <b>Data Protection</b>  | <ul style="list-style-type: none"> <li>• Data protection requirements should be fulfilled</li> <li>• Signatures from all participants are required</li> <li>• Security requirements for server and web interface</li> </ul>   |
|  | <b>Processing</b>       | <ul style="list-style-type: none"> <li>• Attention to data overload</li> <li>• Access to data during the experiment</li> <li>• Attention to data processing errors</li> </ul>   |
|  | <b>Data</b>             | <ul style="list-style-type: none"> <li>• Unique trip IDs important</li> <li>• Important to get all data collected</li> <li>• Attention to data formats</li> <li>• No data wash prior to performance assessments</li> </ul>  |
|  | <b>Cooperation</b>      | <ul style="list-style-type: none"> <li>• Important with direct contact to specialists, technicians and participants</li> <li>• Awareness of business secrets</li> </ul>   |
|  | <b>Technology</b>       | <ul style="list-style-type: none"> <li>• Use reference equipment for comparisons</li> <li>• Get failure rates if possible</li> <li>• Attention to defect units during operation</li> <li>• Pre-test technology prior to trial execution</li> </ul>                          |

**Table 8.2:** Guidelines for GNSS-based Road Charging Trials.



### 8.3.2 GNSS-based Road Charging in Denmark

In Denmark, different road charging schemes and solutions have been discussed during the last decade. Based on the performance assessments conducted in this PhD study, the literature study presented and previous work with the AKTA experiment, this thesis proposes some guidelines for a GNSS-based intelligent road charging system in Denmark.

In Europe different GNSS-based charging schemes exist (refer to Chapter 2), however none of these are based on cumulative GNSS-based charging. Both the Swiss LSVA and the German truck tolling schemes employ GPS to provide continuous vehicle position information, although both of the schemes determine the driven distances by other means. Cumulative road charging schemes are generally considered as complex and risky systems due to the technology dependency. As seen from the assessment results, the vehicle location performance might be good for one type of road charging schemes while inaccurate for others. This is due to the different charging schemes having different requirements depending on charging objective, the scale of the system and how the charge is to be calculated.

This thesis proposes some guidelines in relation to the most commonly discussed charging schemes. Table 8.3 lists the guidelines proposed by this thesis. The guidelines proposed for GNSS-based road charging focus on the technical performance and dependability. The previous chapters have described the technical challenges, performance levels and considerations from the assessments which have formed the basis for the guidelines presented.

## 8.4 Final thoughts...

Previous trials and performance assessments of GNSS-based road charging systems have generally focused on the possibilities of the charging systems rather than on the impossibilities. Often it has not been clearly described which errors and shortages existed in the

| Degree of Detail                |                        | Guidelines  |
|---------------------------------|------------------------|---|
| <b>GNSS-based Road Charging</b> | <b>Zones</b>           | <ul style="list-style-type: none"> <li>• HSGPS OBU with GPRS data transmission</li> <li>• Zone buffers around borders of 100 m</li> <li>• Data processing prior to distance determination</li> <li>• Cumulative distance-based charging</li> <li>• Fault Tolerant Design</li> <li>• Enforcement system for verification</li> </ul>  |
|                                 | <b>Road Segment</b>    | <ul style="list-style-type: none"> <li>• HSGPS OBU with GPRS data transmission</li> <li>• Dead-reckoning support</li> <li>• “Keep it simple” (e.g. main roads only)</li> <li>• Data processing prior to distance determination</li> <li>• Cumulative distance-related charging supported by distance-based charging</li> <li>• Fault Tolerant Design</li> <li>• Enforcement system for validation and verification</li> </ul> |
|                                 | <b>Discrete Events</b> | <ul style="list-style-type: none"> <li>• HSGPS OBU with GPRS data transmission</li> <li>• Large buffers around events</li> <li>• “Keep it simple”</li> <li>• Strategic placement of events</li> <li>• Fault Tolerant Design</li> <li>• Enforcement system for validation and verification</li> </ul>  |

**Table 8.3:** Guidelines for GNSS-based Road Charging in Denmark.

collected data, but instead they have just been excluded as invalid data prior to the assessments which then concluded that more focus should be placed on the errors occurred, the error rates and their importance for the charging process in order to eliminate an even bigger part of the sources of error and obtain a higher system dependability. Although the results were strongly affected by the technical problems during this experiment, it has been deliberate not to exclude faulty and incorrect data. The results presented in this thesis are all based on the collected data in its original form. Data has thereby been represented in its true form as it would be used as input for the automated charge calculation process in a road charging system. The occurrence of technical errors would however be pre-tested and therefore reduced in a real road charging system setup compared to the experimental setup presented in this thesis.

And with these results presented, the always returning question in connection with GNSS-based road charging systems must be addressed: How far are we technically from being able to implement a dependable all-roads-all-vehicles solution? The precise answer would be easy to give if we as researchers could predict the future. However, based on the comprehensive work done both within the literature and as a part of this PhD study, trying to clarify the technological challenges of GNSS-based road charging systems, the best answer is:

*We are close...*

Technically, the results show that significant improvements have happened through the last five years concurrent with the on-going technology development. There are however still some technological challenges to overcome, which to a greater extent are remediated by better collaboration across the many different subject areas. As with many other ITS systems, a successful design, implementation and operation of a system is only achieved when the many different stakeholders understand each other's requirements to the system. The system architecture as a conceptual design

together with the system engineering methodology can help to involve all the different parties in the system development and hence minimize the misunderstandings which at the end can become very costly for the system. GNSS-based road charging systems are very complex systems. It is therefore important to widen the focus from technical challenges and component inaccuracies to a focus of the system dependability as a whole and consider all influencing factors which threaten the dependability of any of the system functions. This can be achieved by carrying out trials and experiments which include the surrounding functions and functionalities supporting the road charging process in GNSS-based road charging systems. In addition, more focus should be put on greater visibility of data results and the methodologies used for different assessments and better sharing of available data.

Ultimately, the final answer to the above question is connected with both the political objectives for the system and the road users' acceptability of GNSS-based road charging systems. Nevertheless, it is still exciting to see where and when the first full-scale GNSS-based road charging system will be initiated.

# Conclusions

---

This chapter presents the main findings of this PhD work on vehicle location determination in GNSS-based road charging systems and provides recommendations for future work.

## 9.1 Conclusions

The results of the technical experiment conducted in this PhD study showed that significant improvements have happened through the last five years. The performance assessment of the vehicle location determination showed that the satellite visibility had improved significantly in Copenhagen between 2003–2008. Both the number of visible satellites and the horizontal dilution of precision had improved substantially, which means that the prerequisites for GNSS-based vehicle location determination had enhanced concurrent with the on-going technology development. In addition, the results showed that the required navigation performance parameters for road transport applications were significantly better than compared to performance assessment results from London in 2002.

There are however still some technical challenges to overcome, which to a greater extent are remediated by better collaboration across the many different subject areas. The technical experiment conducted in this PhD study proved to suffer from different technical challenges which had different impacts on the overall system dependability. Due to these challenges, data was however found to be unreliable for road charging purposes in its existing form. The data includes both inaccurate and incomplete data information, and it was hence concluded that with these high levels of data invalidity and deficiency, data could not be used in its current form as basis for a road charging process. This underlines the importance of a data processing functionality prior to the road charge calculation and usage determination in the road charging process.

While the accuracy requirement in Copenhagen was partly met, the continuity and hence availability required for vehicle location determination suffered from severe gaps in the positioning data. These gaps were due to both satellite unavailability, caused by poor urban signal reception and long receiver acquisition times, and furthermore due to the various technical problems and configuration faults which occurred during the experiment. Based on these results, it was found that the occurred positioning gaps could be classified into three overall categories:

**GPS gaps** which are the minor gaps less than ten minutes primarily caused by GNSS unavailability including time to first fix gaps.

**Downtime gaps** which are the gaps with durations less than a day. These gaps are primarily caused by technical problems or system maintenance resulting in positioning downtime.

**Configuration gaps** are large gaps with durations lasting more than a day. The large gaps are primarily caused by technical configuration faults in the system set-up, resulting in incorrect gap durations or long periods of positioning downtime.

As both the satellite visibility and the positioning accuracy had improved significantly, the results indicated that the main challenges related to vehicle location determination are not as often stated

due to positioning inaccuracies but rather due to a high level of positioning interruptions mainly caused by GPS. The results showed that 63 % of the trips had interruptions in their positioning, with 22 gaps per trip in average. From this performance assessment it was furthermore concluded that the main concerns regarding the unavailability of the vehicle location determination should be how to eliminate the large downtime and configuration gaps and reduce the occurrence of the many GPS gaps.

The simulation analyses of the gap influence on the driven distance determination showed that the driven distance determination function was relatively robust against small gaps in the positioning. The results demonstrated that for both the distance-based and distance-related charging, small gaps had minor if any influence on the determination of distance. The distance-related distance determination was more robust to the occurrence of small interruptions in the positioning information due to both satellite unavailability and time to first fix. In addition, the results demonstrated that with map-matching of positions to the road network, the exact same distance is easier attained for distance-related charging. The distance-related charging was however more dependent of the spatial location of gaps in the position measurements. Furthermore it was found that for both charging methodologies, large gap durations of up to 10 minutes had a severe influence on the driven distance determination as the determined distances were generally underestimated and deviated notably from the true distance. However, the distance-based distance determination was best at reproducing the true distance for trips with large gap durations. On average, the determined distances for the distance-related charging methodology constituted less of the true distance and more importantly, the distance determination was not possible for all trips.

Based on the different assessment results from this thesis, the probabilities of different outcomes were calculated for both charging methodologies. The results showed that since the driven distance determination is most robust to small gaps and small gaps are the most frequent interruptions in the data set, the majority of

trips will result in correct charges. Although the figures presented were not exact, they demonstrated the probability distribution of correct charging with less than  $\pm 1\%$  deviation for the two charging methodologies. In addition it was found that while large gaps have a more significant influence in distance-based charging, the distance-based methodology on average results in less distance deviation from the truth for small and medium gaps. The results from this thesis demonstrated that the road charging process in GNSS-based road charging systems is subject to a severe dependability risk if not considered prior to the system design and deployment. The challenge of meeting the requirement of 99 % of trips with only  $\pm 1\%$  deviation from the driven distance is both to reduce large maximum continuous gaps as these are the most difficult to reproduce, the many small gaps as these are very frequent and to prevent the interruptions caused by system faults. The results from London underlined the importance of choosing the right combination of OBU technology and distance determination methodology in order to obtain the best results for the road charging process. Although few comparable tests exist of the possibilities with internal augmentation systems in connection with road charging systems, the few studies that have been carried out indicate that the results are promising for the use of dead-reckoning systems for GNSS-based road charging.

This thesis therefore concludes that though the vehicle location determination performance is fair, the focus of the system performance concerns should be placed on how future GNSS-based road charging system can be designed to work reliable **with** the occurrence of both data invalidity and data deficiency. It is therefore important to widen the focus from technical challenges and component inaccuracies alone to a focus on the system dependability as a whole. The guidelines proposed for future GNSS-based road charging trials and systems are derived from the technical challenges, problems and considerations learned from this PhD study. There is however still some technological challenges to overcome, which to a greater extent are remediated by better collaboration across the many different subject areas. As with many other ITS systems, a successful design, implementation and operation of a



system is only achieved when the many different stakeholders understand each other's requirements to the system. The system architecture as a conceptual design together with the system engineering methodology can help to involve all the different parties in the system development and hence minimize the misunderstandings which at the end can become very costly for the system.

## 9.2 Main Contributions of this Work

This PhD study deals with assessing the performance of the vehicle location determination function that computes the position measurements used for charging. In the process of answering the research question regarding the challenges and performance of the vehicle location determination, this PhD work has contributed with:

- An overview and classification of existing road charging schemes and enabling road charging technologies.
- An identification of the functional and non-functional requirements to GNSS-based road charging systems.
- A definition of the conceptual design of GNSS-based road charging systems; together with a description of system functionalities and a definition of the high-level functional architecture.
- A description and definition of a functional flowchart for the road charging process within GNSS-based road charging systems.
- An in-depth literature review of GNSS-based case studies regarding road charging.
- New results on vehicle location determination performance based on a technical GNSS-based road charging experiment; together with a classification of the error contributions.
- A methodology for assessing the data reliability prior to ex-

clusion of invalid data records.

- A comparative assessment of the satellite visibility and dilution of precision in Copenhagen between 2003–2008 based on a GIS methodology developed by this PhD study.
- An assessment of the required navigation performance for liability-critical road transport applications; including new methodologies developed by this thesis for assessing the positioning continuity and time to first fix.
- An assessment of the gap influence on driven distance determination based on a new simulation methodology developed for this research.
- A probability assessment based on the results from this thesis of the different charging outcomes for both distance-based and distance-related charging.
- A dependability risk assessment of the different challenges and failures.
- Proposed guidelines for fault tolerant road charging design; and for future GNSS-based road charging trials and systems.

### 9.3 Recommendations for Future Research

This thesis provides a broad foundation for further exploration and research of GNSS-based road charging systems. This PhD work has contributed to the performance assessment of vehicle location determination and of the gap influence on the distance determination. Within these subjects, further studies are proposed below:

**Additional performance parameters** This thesis has focused on assessing the performance in relation to the required navigation performance parameters. In this connection, additional performance parameters could be developed for supporting the assessment of the vehicle location determination

**Accuracy assessment methodology** For accuracy assessments without a reference GNSS receiver, new and improved GIS methodologies could be developed supporting the proximity analyses of fix densities and total outage parameters. Accuracy assessments of the vehicle location determination considering the road dimensions could in addition be interesting.

**Spatial statistics** Research work could be done within spatial statistics. Cluster analyses of position measurements, TTFFs and other factors could provide valuable information to understand the vehicle location determination.

**Simulation methodology** The simulation methodology used for the research presented in this thesis is based on a simplified approach. The methodology could be expanded to include more gap scenarios and for instance combinations of scenarios to simulate and assess the influence of different types of gaps in the positioning.

**GNSS experiments** Learning from the experiences of the technical experiment conducted in this thesis, guidelines are provided for future GNSS-based road charging trials and experiments. Several new studies could be conducted in relation to assessing the integration of GNSS with internal/external augmentation; the possibilities of enhancing the positioning continuity or assessing the system dependability of the entire road charging process in large-scale trials.

In addition, this PhD research has in addition contributed with some overall definitions of the conceptual system design and considerations regarding the system dependability. Within these subjects, further studies are proposed below:

**Road charging requirements** This thesis has classified and provided some generic functional requirements to GNSS-based road charging systems based on the concepts of system engineering. Further studies on decomposing the functional

requirements to the component level could provide beneficial information prior to system design. In addition, a further identification and classification of the non-functional requirements is necessary to develop a well-functioning road charging solution.

**System architecture** As the need for system architectures is becoming more evident within ITS applications, further studies could be conducted to decompose or expand the high-level functional architecture defined by this thesis.

**Fault tolerant charging systems** As discussed in this thesis, complex GNSS-based road charging systems will always include some kind of faults and failures within the system. This thesis has suggested some means of ensuring a fault tolerant road charging system, but further research on failure rates and fault tolerant design in collaboration with other subject areas would provide indispensable information for future deployment of GNSS-based road charging systems.

# Bibliography

---

- AECOM Consult. International Urban Road Pricing. Technical report, Federal Highway Administration, 2006.
- A.L.D. Engineering, 2010. [www.fault-tree-analysis-software.com](http://www.fault-tree-analysis-software.com).
- A. C. Alvarado. *Estimation of Transport Related Demand Elasticities in Mexico City. An Application to Road User Charging*. PhD thesis, Centre for Transport Studies. Imperial College London, United Kingdom, 2008.
- M. André and U. Hammarström. Driving speeds in Europe for pollutant emissions estimation. *Transportation Research Part D*, 5:321–335, 2000.
- R. Arnott. William Vickrey: Contributions to Public Policy. *International Tax and Public Finance*, 5:93–113, 1998. Retrieved October 2008 from <http://fmwww.bc.edu/ec-p/wp387.pdf>.
- V. Ashkenazi, W. Chen, W. Ochieng, C. Hill, and T. Moore. Design of a GNSS: coverage, accuracy and integrity. In *Proceedings of ION GPS-95*, Palm Springs, USA, 1995.
- A. Avizienis, J.-C. Laprie, and B. Randell. Fundamental Concepts of Dependability. In *3rd Information Survivability Workshop (ISW-2000)*, 2000.

- U. Balmer. Practice and Experience with Implementing Transport Pricing Reform in Heavy Goods Transport in Switzerland. In *Essay from the fourth seminar of the IMPRINT-EUROPE Thematic Network: Implementing Pricing Policies in Transport: Phasing and Packaging*, Brussels, May 2003.
- A. Bensky. *Wireless Positioning Technologies and Applications*. Artech House, 2008.
- B. S. Blanchard. *System Engineering Management*. John Wiley & Sons, fourth edition edition, 2008.
- R. Bossom, V. Avontuur, J.-F. Gaillet, G. Franco, and P. Jesty. European ITS Framework Architecture Overview. Technical Report D3.6, European Communities, August 2000.
- R. Brown. Tolling System Architectures. *IET Road Transport Information and Control (RTIC) and ITS United Kingdom Members' Conference*, 2008.
- M. Burnham. Keeping Road User Charging Simple. *TRB 87th Annual Meeting Compendium of Papers DVD*, 2008. Paper No: 08-2272.
- California Department of Transportation. Division of Research & Innovation. System Engineering Guidebook for ITS. Technical Report Version 2.0, U.S. Federal Highway Administration, 2007.
- H. D. Chon, S. Jun, H. Jung, and S. W. An. Using RFID for Accurate Positioning. *Journal of Global Positioning Systems*, 3 (1-2):32–39, 2004.
- R. Cole. The Changing Role of Requirements and Architecture in Systems Engineering. In *Proceedings of the 2006 IEEE/SMC International Conference on System of Systems Engineering*, pages 6–10. IEEE, 2006.
- Columbia University Record. Vickrey One Year Later: Catching Up with a Thinker Way Ahead of His Time., October 1997.

- J. Cosmen-Schortmann, M. Azaola-Saenz, M. Martinez-Olague, and M. Toledo-Lopez. Integrity in urban and road environments and its use in liability critical applications. *Position, Location and Navigation Symposium, 2008 IEEE/ION*, pages 972–983, May 2008. doi: 10.1109/PLANS.2008.4570071.
- D. N. Cottingham, A. R. Beresford, and R. K. Harle. A Survey of Technologies for the Implementation of National-Scale Road User Charging. *Transport Reviews*, 27 (4):499–523, 2007.
- CURACAO. Deliverable D2: State of the Art Review (Interim Month 25). Technical Report Version 4.0, Institute for Transport Studies, University of Leeds., April 2008. [www.curacaoproject.eu](http://www.curacaoproject.eu).
- G. De Ceuster et al. ASSESS Final Report: Assessment of the contribution of the TEN and other transport policy measures to the mid-term implementation of the White Paper on the European Transport Policy for 2010. Technical report, DG TREN, European Commission, 2005.
- V. De Florio. *Application-Layer Fault-Tolerance Protocols*. Information Science Reference (an imprint of IGI Global), 2008.
- G. Deconinck and J. Peperstraete. Fault Tolerance and Dependability in Computer Systems. *Automat. Comput. Appl. Math.*, 6(2):5–14, 1997.
- M. A. Delucchi. The Annualized Social Cost of Motor-Vehicle Use in the United States, based on 1990-1991 Data. Technical report, Institute of Transportation Studies, University of California, 1997.
- A. Demisch, H. Iseki, and B. D. Taylor. TASK A-3: Examining the Linkages between Electronic Roadway Tolling Technologies and Road Pricing Policy Goals. Technical report, California Path Program. Institute of Transportation Studies, University of California, Berkeley., 2009.

- Department of Defense Systems Management College. System Engineering Fundamentals. Technical report, Defense Acquisition University, 2001.
- DfT. Project for the Sustainable Development of Heathrow - Report of the Airport Air Quality Technical Panels. Technical report, Department for Transport, UK, 2006.
- Directorate-General Energy and Transport. CESARE III Project: Interoperability of electronic fee collection systems in Europe. Technical report, EU, 2006.
- C. Drane and C. Rizos. *Positioning Systems in Intelligent Transport Systems*. Artech House, 1998.
- H. Dunlavy. System integrity and user verification of integrity [road pricing and route guidance]. *Technology for Road Pricing and Route Guidance, IEE Colloquium on*, pages 10/1–10/5, May 1991.
- H. Düpow and G. Blount. A Review of Reliability Prediction. *Aircraft Engineering and Aerospace Technology*, 69 (4):356–362, 1997.
- EEA. Traffic noise fact sheet: Exposure and Annoyance. Technical report, European Environment Agency, 2001.
- EEA. Greenhouse gas emission trends and projections in Europe 2007 - Tracking progress towards Kyoto targets. EEA Report No 5/2007, European Environment Agency, 2007.
- J. Eliasson and M. Lundberg. Road Pricing in Urban Areas. Technical Report Vagverket Publication 136E, Swedish National Road Administration and T&E, 2002. Retrieved February 2008 from <http://www.transportpricing.net/download/swedishreport.pdf>.
- ERF. European road statistics. Technical report, European Union Road Federation, 2008.



- European Commission. Green Paper: Future Noise Policy. Technical report, Directorate-General for Energy and Transport, EU, 1996.
- European Commission. Calculating Transport Accident Cost. Final report on the expert advisors to the high level group on infrastructure charging. Technical report, High Level Group on Infrastructure Charging, 1999.
- European Commission. Europe at a crossroads. The need for sustainable transport. Technical report, Directorate-General for Energy and Transport, EU, 2003.
- European Commission. Keep Europe moving. Sustainable mobility for our continent. Mid-term review of the European Commission's 2001 Transport White Paper. Technical report, Directorate-General for Energy and Transport, EU, 2006.
- European Commission. Green Paper: Towards a new culture for urban mobility. Technical report, Directorate-General for Energy and Transport, EU, 2007.
- European Commission. EU Energy and Transport in Figures - statistical pocketbook 2007/2008. Technical report, Directorate-General for Energy and Transport, EU, 2008.
- European Conference of Ministers of Transport. *Managing Urban Traffic Congestion*. OECD Publishing, 2007.
- European Space Agency, April 2011. [www.esa.int](http://www.esa.int).
- J. Evans and N. Williams. Transport for London's Test of Value Added Services to Support DSRC Road Charging Trials, 2009. [www.tfl.gov.uk/](http://www.tfl.gov.uk/).
- J. Evans, N. Patchett, N. Williams, and A. Kowalski. Assessing the use of GPS for congestion charging in London. *Traffic engineering & control*, 46 (3):pp. 98–107, 2005.
- A. Faiz, K. Sinha, M. Walsh, and A. Varma. Automotive Air Pollution: Issues and Options for Developing Countries. *World*

- Bank Policy and Research. The World Bank, Washington DC, Working Paper WPS 492, 1990.*
- R. I. Faulconbridge and M. J. Ryan. *Engineering a System: Managing Complex Technical Projects*. Argos Press, 2005. ISBN: 1-921138-00-9.
- FDOT. Phase I - Systems Engineering Management Plan: A Process Review and Appraisal of the Systems Engineering Capability for the Florida Department of Transportation. Technical Report Version 2, Florida Department of Transportation, 2003.
- Federal Highway Administration. Technologies That Enable Congestion Pricing. Technical report, U.S. Department of Transportation, 2008.
- S. Feng and W. Ochieng. Integrity of Navigation System for Road Transport. In *In Proceedings of the 14th ITS World Congress*, Beijing, China, October 2007.
- K. Forsberg and H. Mooz. The Relationship of Systems Engineering to the Project Cycle. *Engineering Management Journal*, 4(3):36–38, 1992.
- B. Foucher, J. Boullié, B. Meslet, and D. Das. A Review of Reliability Prediction Methods for Electronic Devices. *Microelectronics Reliability*, 42:1155–1162, 2002.
- T. Gärling and G. Schuitema. Travel Demand Management Targeting Reduced Private Car Use: Effectiveness, Public Acceptability and Political Feasibility. *Journal of Social Issues*, 63(1): 139–153, 2007.
- Geospatial Modelling Environment, 2010. Retrieved June 2010 from <http://www.spatialecology.com/gme/>.
- O. Gietelink, J. Ploeg, B. De Schutter, and M. Verhaegen. Vehil: A test facility for validation of fault management systems for advanced driver assistance systems. In *Proceedings of the 1st IFAC Symposium on Advances in Automotive Control, Salerno, Italy*, pages pp. 410–415, Salerno, Italy, 2004.

- GMAR. GNSS Metering Association for Road User Charging, 2010. Retrieved May 2010.
- A. Goldsmith. *Wireless Communications*. Cambridge University Press, 2005. Stanford University.
- J. A. Gomez-Ibanez and K. A. Small. *Road Pricing for Congestion Management: A Survey of International Practice*. National Academy Press, Washington, 1994.
- P. J. Gonzalez. A Guide to Configuration Management for Intelligent Transportation Systems. Technical report documentation page, Prepared for US Department of Transportation by Mitretek Systems, Inc., Retrieved February 2010 from [www.rita.dot.gov](http://www.rita.dot.gov) 2002.
- P. Goodwin. The Economic Cost of Congestion. UCL Eprints, University College London, 2004. Retrieved November 2008 from <http://eprints.ucl.ac.uk/1259/>.
- P. D. Groves. *Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems*. Artech House, 2008.
- B. Grush, J. Cosmen-Schortmann, C. Hamilton, and M. Martinez-Olague. GMAR Standard Performance Definitions for GNSS Road Use Metering. In *Proceeding of the 16th World Congress on Intelligent Transport Systems*, 2009.
- T. D. Hau. Economic Fundamentals of Road Pricing: A Diagrammatic Analysis. *World Bank Policy Research. The World Bank, Washington D.C.*, Working Paper Series WPS 1070:1–96, 1992.
- HM Treasury. Modernising the Taxation of the Haulage Industry - Progress Report One. Technical report, The Public Enquiry Unit, 2002. Retrieved December 2008 from [www.hm-treasury.gov.uk](http://www.hm-treasury.gov.uk).
- B. Hofmann-wellenhof, H. Lichtenegger, and E. Wasle. *GNSS - Global Navigation Satellite Systems: GPS, GLONASS, Galileo & more*. SpringerWienNewYork, 2008.

- IEEE 1474-2000. IEEE Recommended Practice for Architectural Description of Software-Intensive Systems, 2000.
- P. Ieromonachoua, S. Pottera, and J. Warrenb. Norways urban toll rings: Evolving towards congestion charging? *Transport Policy*, 13:367–378, 2006.
- International Transport Forum. Conference on Road Charging Systems: Technology Choice and Cost Effectiveness. In *Road Charging Systems - Technology Choice and Cost Effectiveness. Summary and Conclusions.*, 2006.
- S. Jaensirisak. Urban Road Pricing: From Theory to Practice. In *Proceedings of the Eastern Asia Society for Transport Studies.*, 2003.
- A. Jakob, J. L. Craig, and G. Fisher. Transport cost analysis: A case study of the total costs of private and public transport in Auckland. *Environmental Science & Policy*, 9(Issue 1):55–66, February 2006.
- C. Jakobssona, S. Fujii, and T. Garling. Determinants of private car users acceptance of road pricing. *Transport Policy*, 7:153–158, 2000.
- A. B. O. Jensen, M. Zabic, H. M. Overå, B. Ravn, and O. A. Nielsen. Availability of GNSS for Road Pricing in Copenhagen. In *Proceedings of the 18th International Technical Meeting of the Satellite Division of the Institute of Navigation-ION GNSS 2005*, pages 2951–2961. The Institute of Navigation, 2005. Presented at: ION GNSS 2005 : Long Beach, California. USA, 2005. Note: Best Presentation Award.
- R. Kalauskas, B. D. Taylor, and H. Iseki. TASK A-1: Motivations Behind Electronic Road Pricing. What is the Driving Force Behind the Worldwide Rise in Tolling? A Review of Innovative Road Pricing from Across the Globe. Technical report, California PATH Program. Institute of Transportation Studies, University of California, Berkeley, 2009.

- E. D. Kaplan and C. J. Hegarty. *Understanding GPS Principles and Applications*. Artech House, second edition edition, 2006.
- Kapsch Trafficcom. Austrias Nationwide Truck Tolling System. Retrieved May 2010 from <http://www.kapsch.at>.
- F. H. Knight. Some Fallacies in the Interpretation of Social Cost. *The Quarterly Journal of Economics*, 38:582–606, 1924.
- KonSULT. A Decision-Makers Guidebook, 2009. [www.konsult.leeds.ac.uk/](http://www.konsult.leeds.ac.uk/).
- T. Kos, M. Grgic, and G. Sisul. Mobile User Positioning in GSM/UMTS Cellular Networks. In *Proceedings of the International Symposium ELMAR-2006 focused on Multimedia Signal Processing and Communications*, pages 185–188, June 2006.
- Krak. Kraks Danske Vejnet. Professionel - Rute (In Danish). Documentation, Kraks Forlag AS, Kraks Kort & GIS. Virumgårdsvej 21. 2830 Søborg., September 2004.
- O. Kveiborg. Transportens eksterne omkostninger. Et litteraturstudie af værdisætningsmetoder mhp. internalisering (in Danish). Technical report, Danish Environmental Protection Agency, 2001.
- A. Lewis, M. Purvis, J. Sambells, and C. Turner. *Beginning Google Maps Applications with Rails and Ajax From Novice to Professional.*, chapter Chapter 10: Lines, Lengths, and Areas, pages p.261–285. Apress, 2007.
- T. Litman. Transportation Cost Analysis for Sustainability. [www.vtpi.org/sustain.pdf](http://www.vtpi.org/sustain.pdf), 1999.
- T. Litman. Transportation cost and benefit analysis: Techniques, estimates and implications. Technical Report Second Edition, Victoria Transport Policy Institute, 2009. Retrieved October 2008 from [www.vtpi.org](http://www.vtpi.org).
- P. Loukopoulos. A classification of travel demand management measures. In *Threats to the quality of urban life from car traffic: Problems, causes, and solutions*. Elsevier, 2007.

- M. Maibach, C. Schreyer, D. Sutter, H. v. Essen, B. Boon, R. Smokers, A. Schroten, A. Doll, B. Pawlowska, and M. Bak. Handbook on estimation of external costs in the transport sector. internalisation measures and policies for all external cost of transport (impact). Technical Report Version 1.1, CE Delft, February 2008.
- MapFlow. Analysis of the TFL GPS OBU Data. Technical report, Final Report prepared for the Dutch Ministry of Transport. Different Payment for Mobility Project Organisation., 2007. Retrieved February 2010 from [www.verkeerenwaterstaat.nl](http://www.verkeerenwaterstaat.nl).
- D. Matheson. The Challenges of a True Distance Approach to Road Charging. In *Proceedings of the European Transport Conference*, 2005.
- A. D. May. Road pricing: An international perspective. *Transportation*, 19:313–333, 1992.
- M. D. Meyer, T. F. Humphrey, C. M. Walton, K. Hooper, R. G. Stanley, C. K. Orski, and P. A. Peyser. *A Toolbox for Alleviating Traffic Congestion*. Institute of Transportation Engineers Publications, 1st edition edition, 1989.
- Ministry of Transport. Boeredygtig transport - bedre infrastruktur (in Danish). Technical report, The Danish Government, December 2008.
- P. Misra and P. Enge. *Global Positioning System: Signals, Measurements, and Performance*. Ganga-Jamuna Press, Lincoln, Mass., USA, 2nd edition, 2006.
- P. Misra, B. P. Burke, and M. M. Pratt. GPS Performance in Navigation. In *Proceedings of the IEEE*, volume VOL. 87, January 1999.
- S. L. Morgan and C. G. Waring. Guidance on Testing Data Reliability. Technical report, City of Austin, Texas, USA, 2004.
- S. Næss-Schmidt, U. Møller, and H. N. Jensen. Grøn omlægning af bilbeskatningen (in Danish). Technical report, Dansk Energi, March 2010.

- National Policing Improvement Agency. The Management and Use of Automatic Number Plate Recognition. Technical report, Association of Chief Police Officers, 2009.
- New Civil Engineer. Government collapse scuppers Dutch road pricing plans. webpage, April 2010. [www.nce.co.uk](http://www.nce.co.uk).
- NGA GPS Division. National Geospatial-Intelligence Agency, 2010. [www.navcen.uscg.gov](http://www.navcen.uscg.gov).
- O. Nielsen and C. Würtz. Using GPS for road pricing: Experiences from Copenhagen. In *Proceedings 19th World Congress and Exhibition on Intelligent Transport Systems and Services*, number Session: PS 117, 2003. Presented at: 19th World Congress and Exhibition on Intelligent Transport Systems and Services : Madrid, Spain, 2005.
- O. A. Nielsen. The AKTA road pricing experiment in Copenhagen. In *Proceedings of the European Transport Conference*, Strasbourg, France, 2002.
- O. A. Nielsen. Analyse af trængsel og hastigheder vha. GPS-data (in Danish). In *Proceedings of Trafficdays 2003*, Aalborg, Denmark, 2003.
- O. A. Nielsen and R. M. Jørgensen. Map-matching algorithms for GPS data Methodology and test on data from the AKTA road pricing experiment in Copenhagen. In *Proceedings of the World Conference on Transport Research Society (WCTRS)*., number Paper 1435, Istanbul, Turkey., July 2004.
- O. A. Nielsen and M. V. Sørensen. *Road Pricing, the Economy and the Environment*, chapter The AKTA Road Pricing Experiment in Copenhagen, pages 93–109. Advances in Spatial Science. Springer Berlin Heidelberg, 2008.
- R. B. Noland. A review of the evidence for induced travel and changes in transportation and environmental policy in the US and the UK. *Transportation Research Part D*, pages 1–26, 2002.

- R. B. Noland and L. L. Lem. A review of the evidence for induced travel and changes in transportation and environmental policy in the US and the UK. *Transportation Research Part D*, 7(1): 1–26, 2002.
- W. Ochieng. Advanced Transport Telematics Positioning Requirements: An assessment of GPS Performance in Greater London. *The Journal of Navigation*, 52:342–355, 1999.
- W. Ochieng and K. Sauer. Urban road transport: performance of the global positioning system after selective availability. *Transportation Research Part C*, 10 (3):171–187, 2002.
- W. Ochieng, R. Noland, J. Polak, P. J-H., L. Zhao, D. Briggs, A. Crookell, R. Evans, M. Walker, and W. Randolph. Integration of GPS and Dead Reckoning for Real Time Vehicle Performance and Emissions Monitoring. *The GPS Solutions Journal*, 6(4):229–241, 2003a.
- W. Ochieng, J. Polak, R. Noland, J. Y. Park, L. Zhao, D. Briggs, J. Gulliver, A. Crookell, R. Evans, M. Walker, and W. Randolph. Integration of GPS and dead reckoning for real-time vehicle performance and emissions monitoring. *GPS Solutions*, 6 (4):pp. 229–241, 2003b.
- W. Ochieng, R. North, M. Quddus, and R. Noland. Technologies to Measure Indicators for Variable Road User Charging. In *Transportation Research Board 87th Annual Meeting*, 2008.
- H. Ohno, T. Suzuki, Y. Yamaguchi, S. Okamoto, and K. Ilzuka. Development of the Next Generation Road Pricing System with GPS Technology. *Technical Review*, 44 (2), 2007.
- V. Pearce. Conduct a Requirements Analysis to determine the most appropriate ITS telecommunications solution. Experiences from the Department of Transportation (DOTS) of multiple states in selecting telecommunications options. In *Communications for Intelligent Transportation Systems - Successful Practices: A Cross-Cutting Study*. U.S. Department of Transportation, Federal Transit Administration and Federal Highway Administration (USA)., 2000.



- K. Persad, C. M. Walton, and S. Hussain. Toll Collection Technology and Best Practice. Technical report, Center for Transportation Research, University of Texas at Austin., 2006. Revised 2007.
- A. T. Pickford and P. T. Blythe. *Road User Charging and Electronic Toll Collection*. Artech House, 2006.
- A. C. Pigou. *The Economics of Welfare*. Macmillan, London., 1920.
- Z. Pribanic, G. Knezevic, and G. Sepuka. Road toll collection in the Republic of Croatia with a special emphasis on interoperability. In *Proceeding of the 34th Study and Information Days ASECAP*, 2006.
- M. A. Quddus, W. Y. Ochieng, and R. B. Noland. Current map-matching algorithms for transport applications: State-of-the art and future research directions. *Transportation Research Part C*, 15:312328, 2007.
- J. Rajnoch. Review of Different Approaches to Distance Based Charging. In *Proceedings of ITS European congress*, 2008.
- J. Ranchordas and A. Lenaghan. A flexible framework for using positioning technologies in location-based services. In *Proc. EUROCON 2003. Computer as a Tool. The IEEE Region 8*, volume 2, pages 95–98, Sept. 22–24, 2003.
- M. Rapp and U. Balmer. The Swiss Distance Related Heavy Vehicle Fee (LSVA) - A Novel Approach to Area-Wide Road Charging. Rapp Trans, AG, Basel, 2004, 2004.
- RCI Project Consortium. Road Charging Interoperability (RCI), November 2008. [www.ertico.com](http://www.ertico.com).
- M. Reibel. Geographic Information Systems and Spatial Data Processing in Demography: a Review. *Population Research and Policy Review*, 26 (5-6):601–618, 2007.

- Road User Charging Interest Group. White Paper - Technology Options for Road Pricing in the UK. Technical report, ITS United Kingdom, 2007.
- J. Rouwendal and E. T. Verhoef. Basic economic principles of road pricing: From theory to applications. *Transport Policy*, 13(2): 106 – 114, 2006.
- A. Sage. Future Positioning Technologies and their Application to the Automotive Sector. *The Journal of Navigation*, 54 (3): 321–328, 2001.
- A. P. Sage and J. E. J. Armstrong. *Introduction to Systems Engineering*. John Wiley & Sons, 2000.
- N. Samama. *Global Positioning: Technologies and Performance*. John Wiley and Sons, 2008.
- F. Schwarz-Herda. Toll Collection in Austria. In *Proceedings of the PIARC Seminar on Road Pricing with emphasis on Financing, Regulation and Equity*, Mexico, April 2005.
- K. Sheridan. State of the Art in GNSS-Based Road Pricing. Technical Report Issue 1.B, SIGNATURE, 2009.
- R. W. Sinnott. Virtues of the Haversine. *Sky and Telescope*, 68 (2)(2):p.184, 1984.
- R. Smeed. Road Pricing: The Economic and Technical Possibilities. The Smeed Report, Ministry of Transport. London, 1964.
- P. A. Sorensen and B. D. Taylor. Review and Synthesis of Road-Use Metering and Charging Systems. Technical report, UCLA Institute of Transportation Studies, 2006.
- W. Stallings. *Wireless Communications and Networks*. Prentice Hall, 2nd edition edition, 2002.
- U. Stopka. The Potential of Wireless Communication, Positioning and Navigation Systems for Improving the Management of Commercial Vehicle Operations. *Mechanics Transport Communications*, 3:8–14, 2008.

- S. Subramanya and B. K. Yi. Mobile communications - an overview. *IEEE Potentials*, 24 (5):36–40, December 2005.
- A. Sumalee, S. Shepherd, and A. May. Road user charging design: dealing with multi-objectives and constraints. *Transportation*, 36:167–186, 2009.
- T-Systems Satellic. KMP in The Netherlands: Report of T-Systems Satellic as contribution to the Market Consultation (Phase 2). Technical report, Ministerie van Verkeer en Waterstaat, 2006.
- S. Taghipour, M. R. Meybodi, and A. Taghipour. An Algorithm for Map Matching For Car Navigation System. In *Proc. 3rd International Conference on Information and Communication Technologies: From Theory to Applications ICTTA 2008*, pages 1–5, Apr. 7–11, 2008. doi: 10.1109/ICTTA.2008.4529959.
- G. Taylor and G. Blewitt. *Intelligent Positioning. GIS-GPS Unification*. John Wiley & Sons, 2006.
- T&E. Can you hear us? Why it is finally time for EU to tackle the problem of noise from road and rail traffic. Technical report, European Federation for Transport and Environment, 2001.
- TfL. London Congestion Charging Technology Trials Stage 1 Report. Technical report, Transport for London., 2005. London.
- TfL. London Congestion Charging Technology Trials Stage 2 Final Report. Technical report, Transport for London, 2006a. London.
- TfL. Distance-based Charging. Report in Transport for Londons (TfL) GPS OBU Trial. Technical report, Transport for London. Congestion Charging (Traffic & Technology)., 2006b. London.
- TfL. London Congestion Charging Technology Trials Stage 3 Final Report. Technical report, Transport for London., 2008. London.
- The Danish Data Protection Agency. Retrieved January 2010 from [www.datatilsynet.dk](http://www.datatilsynet.dk).

- R. Toledo-Moreo, B. U. beda, J. Santa, M. A. Zamora-Izquierdo, and A. F. G´omez-Skarmeta. An Analysis of Positioning and Map-Matching Issues for GNSS-Based Road User Charging. In *Proceedings of 13th International IEEE Annual Conference on Intelligent Transportation Systems*, Madeira Island, Portugal, September 2010.
- Toll Collect. Truck Toll in Germany: User Information, 2007. Retrieved November 2009 from [http://www.toll-collect.de/pdf/benutzerinformation/web\\_einfuehrungstex\\_gb.pdf](http://www.toll-collect.de/pdf/benutzerinformation/web_einfuehrungstex_gb.pdf).
- T. Tsekeris and S. Voß. Design and evaluation of road pricing: state-of-the-art and methodological advances. *NETNOMICS*, 10 (1): 5–52, April 2009.
- K. Tsunokawa and C. Hoban. Roads and the Environment: A handbook. Technical Paper No. 376, World Bank, Washington, DC, 1997.
- UN. World urbanization prospects: The 2005 revision. Technical report, Department of Economic and Social Affairs. Population Division. United Nations, 2006.
- US Army Corps of Engineers. *NAVSTAR Global Positioning System Surveying*, February 2011. Engineering Manual, EM-1110-1-1003.
- US DoD. Global Positioning System Standard Positioning Service Performance Standard., 2001.
- W. Vickrey. Principles of Efficient Congestion Pricing, June 1992. Retrieved February 2009 from <http://www.vtpi.org/vickrey.htm>.
- W. S. Vickrey. Pricing in Urban and Suburban Transport. *American Economic Review: Papers and Proceedings*, 53 (2):452–465, 1963.
- Victoria Transport Policy Institute. Online TDM Encyclopedia, 2009. Retrieved January 2009 from [www.vtpi.org](http://www.vtpi.org).
- D. Vonk Noordegraaf, B. Heijligers, O. van de Riet, and G. van Wee. Technology Options for Distance-based Road User Charging Schemes. *TRB 88th Annual Meeting Compendium of Papers DVD*, 2009. Paper No: 09-2477.

- D. Vrhovski, T. Moore, and L. Bennett. GNSS-based Road User Charging. *The Journal of Navigation*, 57:1–13, 2004.
- R. Walker and D. Naberezhnykh. Techniques for Assessment of Road User Charging and Global Navigation Satellite Systems data: Final Report. Technical report, Transport Research Laboratory, 2009.
- B. Wieland. The German HGV-toll. *European Transport: International Journal of Transport Economics, Engineering and Law*, 31: 118–118, 2005.
- H. Worrall. Technology and Pricing: Cause or Effect? In *International Perspectives on Road Pricing. Report of the Committee for the International Symposium on Road Pricing*. Transportation Research Board, Key Biscayne, Florida, 2003. Retrieved May 2009 from <http://onlinepubs.trb.org/onlinepubs/conf/CP34roadpricing.pdf>.
- M. Zabic. A GIS-analysis of GPS quality for Road Pricing (in Danish). Master's thesis, Technical University of Denmark, Centre for Traffic and Transport, 2004.
- M. Zabic. GPS & Roadpricing (in Danish). In *Proceedings of Traffic Days 2005*, 2005. Aalborg, Denmark.
- M. Zabic. An ArcGIS analysis of Stand-alone GPS quality for Road Pricing. In *Proceedings of ESRI International User Conference*, San Diego, CA, USA, 2006.
- M. Zabic. Road Charging in Copenhagen: A Comparative Study of the GPS Performance. In *Proceedings of the 16th World Congress on Intelligent Transport Systems*, Stockholm, Sweden, 2009.
- M. Zabic. Teknologiske udfordringer ved positionsbestemmelse i GNSS-baserede kørselsafgiftssystemer (in Danish). In *Proceedings of Traffic Days 2011*, 2011a. Aalborg, Denmark.
- M. Zabic. A High-Level Functional Architecture for GNSS-based Road Charging Systems. In *Proceedings of the 18th World*

*Congress on Intelligent Transport Systems*, 2011b. Orlando, Florida, USA.

- M. Zabic and O. A. Nielsen. An Analysis of Stand-alone GPS Quality and Simulated GNSS Quality for Road Pricing. In Brebbia and Dolezel, editors, *Urban Transport XII : Urban Transport and the Environment in the 21st century*, pages 859–868, Southampton, UK, 2006. WIT Press. ISBN 1-84564-179-5. Presented at: Urban Transport 2006 : Prague, CZ, 2006.
- F. Zijderhand, W. Van Nifterick, and A. Zwiers. Anders Betalen voor Mobiliteit. Accuracy and reliability of distance and position measurements by GNSS systems. Research Assignment 3. Technical report, ARS Traffic & Transport Technology, 2006. The Hague, Netherlands.

## Haversine Formula

---

### A.1 Determination of Distance Between Two Points

The distance between two position measurements were calculated by the Haversine Formula [[Sinnott, 1984](#)]. This formula for distance determination between two points in spherical coordinates (longitude and latitude) are given in the following:

$$dlon = lon2 - lon1$$

$$dlat = lat2 - lat1$$

$$a = (\sin(dlat/2))^2 + \cos(lat1) \cdot \cos(lat2) \cdot (\sin(dlon/2))^2$$

$$c = 2 \cdot \text{atan2}(\sqrt{a}, \sqrt{1-a})$$

$$d = R \cdot c$$

Where  $R = 6,367$  km (Radius of the Earth).

The Haversine formula is only an approximation as the Earth is

not a perfect sphere. The Earth radius  $R$  varies from 6,356.78 km at the poles to 6,378.14 km at the equator. Hence, there are small corrections typically on the order of 0.1 % [[Lewis et al., 2007](#)].



DTU Transport performs research and provides education on traffic and transport planning. It advises the Danish Ministry of Transport on infrastructure, economic appraisals, transport policy and road safety and collects data on the transport habits of the population. DTU Transport collaborates with companies on such topics as logistics, public transport and intelligent transport systems.

DTU Transport  
Department of Transport  
Technical University of Denmark

Bygningstorvet 116B  
Bygning 115  
DK-2800 Kgs. Lyngby  
Tel. +45 45 25 65 00

[www.transport.dtu.dk](http://www.transport.dtu.dk)